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AN INDUSTRIAL WORKFLOW TO MINIMIZE PART
DISTORTION FOR MACHINING OF LARGE MONOLITHIC
COMPONENTS IN AEROSPACE INDUSTRY

A THESIS

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Abstract

Part distortion caused by inevitable residual stresses results in recurring concession, rework and scrap, which worth millions of Euro in the aircraft development and manufacturing life cycle.

This thesis is the result of a collaborative work between UNIVERSITY OF GUANAJUATO (Mechanical Engineering Department), AIRBUS OPERATIONS S.A.S. and KAISER ALUMINUM. An overall approach to aerospace industry is explored into the first chapter; materials used in aerospace industry and main manufacturing processes involved in structural aircraft components are described, introducing the reader to the work developed into this thesis.

An accurate process to predict distortion after machining of large monolithic components from rolled plates is developed going from characterization and measurement of residual stress (L and LT directions in rolled plates) by layer removal method; data processing to fit mathematical functions (sum-of-cosine function) one for each direction, obtaining 6 coefficients by function; numerical simulations and post-processing results management to find optimal position of the part into the rolled plate. This process is designed to empower manufacturing engineers at the shop floor level. Open source software is used for pre-processing, during the computational numerical analysis and post-processing data analysis; a module of FreeCAD is developed for comfort visual and ease use for user; CalculiX subroutine is developed to residual stress mapping and FEM simulation; R code is generated to visually present the results through plots with position variables and distortion result; sensitive analysis of positioning and residual stress factors is shown by these plots.

A representative case study is extensively explored following the proposed workflow, validation of the predicted distortion of the proposed geometry is executed, machining the part in high distortion position and optimal position into the plate; machining process and distortion measurements were performed at the University of Guanajuato workshop. Due several factors that determine the properties of the aluminum plates (micro-structure, manufacturing processes variables, position into the main plate and non-identified variables), the plates are produced in batches, each one with specific properties. Uncertainty propagation of material properties is imitated with $\pm 10\%$ variation of each coefficient from the fitted functions. The variation of the 12 coefficients which defines residual stresses profiles (L and LT directions) is analyzed for the optimal solution of the case study in a $1/16$, two levels, fractional factorial design; this experiment has resolution VI with 256 runs and not confounding for interactions.

Results from both experimental parts show high agreement with predicted behavior in distortion of the case study in the simulations, having congruence in distortion profiles complementing with good accuracy in distortion values. Results from the fractional factorial design show the forth coefficient of the residual stress function for both directions as the coefficients with more influence, concentrating 75% of the results into low deformation values (maximal distortion in Z direction: $0.125 \text{ mm} \pm 0.125 \text{ mm}$).

Keywords

Machining Distortion, Residual Stress of Rolled Plates, Modeling, Simulation, Design of Experiments, FreeCAD, CalculiX, R.

Dedictory

This thesis work is dedicated to my mother, Gloria, who has been a source of encouragement and inspiration to me throughout my life, for the unconditional support on developing myself professionally and the opportunity to travel and learn from the world, expanding my mind to reach my dreams and realize my potential and capabilities, being a professional engineer with the capacity of contribution to our society.

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Introduction & Justification

Distortion after machining of large monolithic structural components is a common problem in manufacturing life cycle in aerospace industry; after machining, the desired geometry suffers a deviation when releasing from fixture. This deviation from intended geometry is not due to machining tolerance, dimensional imprecision or over/under-machined. Reference [3] presents distortion as major challenge in airframe industry, costing billion of losses in profit yearly.

Reference [4] shows a study by Boeing, based on four aircraft programs, estimating the rework and scrap costs linked to part distortion comes to in excess of 290 million dollars. Reference [5] estimates an economic loss of €850 million in Germany automotive and aeronautic industries due part distortion.

It is extendedly known that distortion comes from several factors, residual stresses in bulk material and the location of the part into the billet of which it was machined are analyzed as important variables in Reference [6]; the part design is also importantly driven in Reference [7]; machining induced residual stresses where machining variables as cutting speed, feed speed, revolutions per minute and deep of cut by run are crucial.

Metallic alloys are widely used in aerospace structural components; these components are often machined into large thin wall or web components. Materials before forming came in rolled plates, forgings, extrusion or casting where up to 90 to 95% of the material can be removed. As mentioned, an important variable are the characteristic residual stresses into the pre-machined material, generated by several manufacturing processes (quenching, stretching, forging, extrusions, casting, welding (Reference [8]), machining, forming, etc.). These manufacturing processes are usually complex combinations of mechanical deformation with heat transfer involved causing metallurgical changes.

This thesis work is addressed to machined structural components from rolled plates. A rolled plate has residual stresses due its manufacturing processes, starting with the mix of different alloying elements, it is then melted and casted into an ingot to be cooled, later it is heated, rolled, quenched to achieve the physical and mechanical properties needed for aerospace use. All these processes induce undesirable high levels of residual stresses caused by the heat flux and high temperature gradients through the plate. Reference [9] describes quenching process, where the extreme conditions usually induce thermal residual stresses at yield stress magnitude, causing high residual stresses and moreover, causing distortion or cracking. After quenching, rolled plate needs residual stress relief, this is done by stretching the plate, Reference [10] describes this process, it is mechanically stretched in the rolling direction to 1.5 to 3% plastic deformation at room temperature. The present work proposes an industrial solution to reduce as much as possible part distortion of structural parts after machining including I) determination of bulk residual stresses in rolled plate; II) data processing to create residual stress profiles; III) numerical simulation to determine optimized part location for minimal distortion.

Objective

The objective of this thesis work is to provide a trustworthy workflow to predict machining distortion due residual stresses in rolled plates, developing detailed steps ease to follow by manufacturing engineers at the shop floor level.

A reliable method to measure residual stress profiles in L and LT directions of rolled plate is required; data treatment of this measurements to get a mathematical function is needed for FEM simulations.

Open source software is expected to be adapted, programing in Python and Fortran languages, developing a full integrated module in FreeCAD, with an efficient interface and post-processing data analysis.

The final objective is to measure the distortion prediction capability of the workflow, machining a representative part at the workshop of the University of Guanajuato. Comparisons between simulations and machined part are expected to be discussed for method validation.

2 levels, fractional factorial design is expected to be applied for uncertainty propagation analysis.

I Aerospace Structures

Into this chapter, an overall approach to aerospace industry (Materials & Manufacturing Processes) is explored based on [1], [2] and [18]; introducing the reader to the work developed into this thesis; representative figures and general information as well as important ideas from these references are treated and exposed in words and experience of the author of this thesis work.

Materials in Aerospace Industry

The development in aerospace technology strongly depends on the materials used in every structural or jet engine component. The success in aerospace mechanical design is determined by the correct choice of materials; this choice also influence the manufacturing technology used for each component, the production costs and final price of the aircraft and its life cycle, fuel consumption (heavier elements waste more fuel), power and general efficiency of the engine, operation and maintenance, safety, greenhouse gas emissions, recycling of elements at the end of life cycle.

Some of the critical components of an helicopter are the fuselage, tail boom and rotor blades; for an aircraft some examples of structural components are the wings, fuselage, empennage and landing gear; in aerospace, optimal materials are chosen for the airframe, skins and thermal isolation tiles of spacecrafts. These elements are subjected to complex loads during departure, flight and landing, assuring safety and stability. Other complex materials are implemented in engine applications, where high temperatures in the turbine influence in most of the important resistance properties of materials; Turbine blades carry loads in order to generate thrust to propel the aircraft. Oxidation and corrosion increase with temperature, reducing life cycle of these elements.

In aerospace material applications it is important a deep understanding of material properties; physical properties (special interest in lower density materials), mechanical properties (optimal stiffness, strength and toughness), chemical properties (materials resistant to corrosion and oxidation), thermal properties (heat capacity, thermal conductivity, thermal expansion) and electrical properties (focusing on electrical conductivity). To understand these properties is necessary to know the composition and structural organization of the materials and even further how this influence and control their properties. The characterization of the materials must be understood from atomic to structural application level; analyzing microscopical scale of metals it is found that any small precipitation or defect, grain size and grain structure on metallic materials, impacts their properties and susceptibility to fail and fracture. In composite materials the microscopic scale is also important where the fiber organization, arrangement and any small void or delamination influence their properties. Macro scale analysis in materials such the geometry and dimensions are important, it determines how loads are distributed through the material, failure and rupture may occur in a bad distribution or concentration of operational loads. Figure 1 shows the different scale levels for materials analysis.

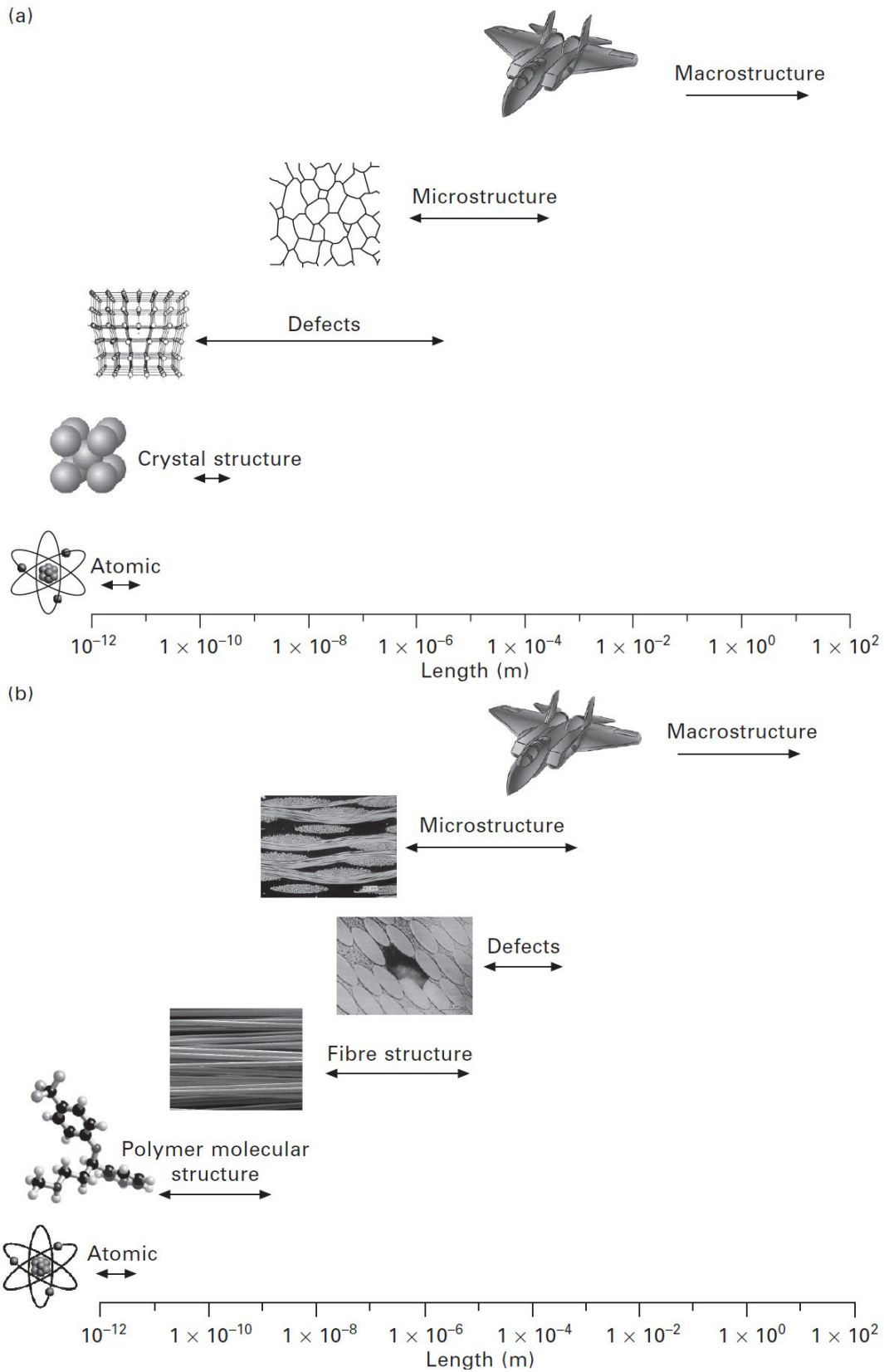


Figure 1: This figure shows the structural factors at different sizes that affects material properties in (a) metals and (b) fibre-polymer composites. [1]

As any other mechanical component, in aerospace design, the material and properties needed for each component depends on the application, supporting loads without notable deformation or rupture, resisting ambient conditions at considerable altitude (pressure, humidity, temperature), resisting corrosion and oxidation at high temperatures without softening. Most aerospace engineering development occurs in the field of materials, for this reason is crucial to understand the science of materials.

Despite the huge and wide variety of available materials, aerospace requirements demands materials with specific combination of properties, limiting the number of useful materials; aerospace materials must have low density, must be rigid, strong, resistant to corrosion and oxidation, durable. It is estimated that less than 0.05% of available materials are suitable for aerospace applications.

The main materials that are suitable for aerospace structural applications are aluminum alloys, titanium alloys, steels and composites. For structural engine applications nickel-based alloys are used. Table 1 shows typical aeronautic materials and key characteristics comparison.

Property	Aluminum	Titanium	Magnesium	High Strenght Steel	Nickel Superalloy	Carbon Fibre Composite
Cost	Cheap	Expensive	Medium	Medium	Expensive	Expensive
Weight (Density)	Light	Medium	Very Light	Heavy	Heavy	Very Light
Stiffness (Elastic Modulus)	Low/Medium	Medium	Low	Very Hight	Medium	High
Strength (Yield Stress)	Medium	Medium/High	Low	Very Hight	Medium	High
Fracture Toughness	Medium	High	Low/Medium	Low/Medium	Medium	Low
Fatigue	Low/Medium	High	Low	Medium/High	Medium	High
Corrosion Resistance	Medium	High	Low	Low/Medium	High	Very High
High-Temperature creep strength	Low	Medium	Low	High	Very High	Low
Ease of Recycling	High	Medium	Medium	High	Medium	Very Low

Table 1: Grading of aerospace materials on key design factors. [1]

Regarding the functionality of the components in aerospace, a material and geometry are designed for the specific operational propose of each piece. Most commercial aircrafts uses over 60% of aluminum, however the composites materials development pretends to displace metallic alloys and increasingly use composites in aircraft structural components, this is the case of the Boeing 787 that has reached 50% of composite materials and reducing to 44% the metals. In other cases as the F-22 Raptor, there will be more percentage of titanium because this is a military aircraft submit to very high velocities and loads; to reach these velocities it needs to be strong but light at the same time, that is why it is used titanium in critical components but also a big percentage of composites is used to reduce the mass of the aircraft. Fig 2 shows a general panorama of the percentage of materials used in some commercial and military aircrafts.

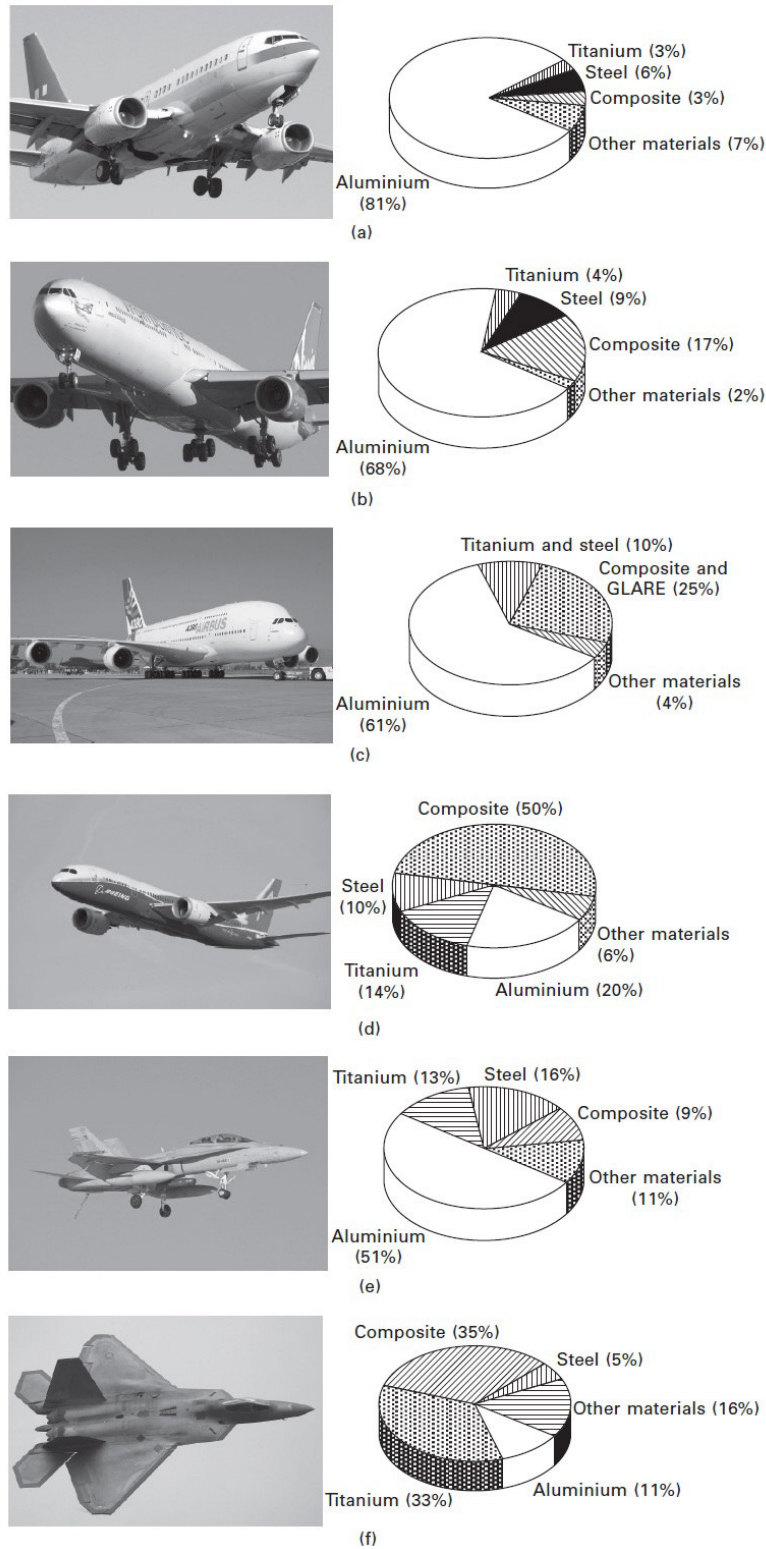


Figure 2: This figure shows the structural materials and their weight percentage used in the airframes of civilian and military aircraft. (a) Boeing 737, (b) Airbus 340-330, (c) Airbus A380, (d) Boeing 787, (e) F-18 Hornet (C/D), (f) F-22 Raptor. [1]

The design engineer has the responsibility to make the choice of material for each structural or engine component, the correct functionality and safety of the aircraft strongly depends on these choices, these choices are not a guesswork, there are many specific considerations and requirements that must be covered to successfully develop an aircraft. Table 2 indicates the main requirements to choose a material for aerospace components, all these requirements must be covered as best as possible depending on the function and location of the components.

Costs	Purchase cost. Processing costs, including machining, forming, shaping and heat treatment costs. In-service maintenance costs, including inspection and repair costs.
Availability	Plentiful, consistent and long-term supply of materials.
Manufacturing	Ease of manufacturing Low-cost and rapid manufacturing processes.
Density	Low specific gravity for lightweight structures.
Static mechanical properties	Stiffness (elastic modulus). strength (yield and ultimate strength).
Fatigue durability	Resistance against initiation and growth of cracks from various sources of fatigue. (e.g. stress, stress-corrosion, thermal, acoustic)
Damage tolerance	Fracture toughness and ductility to resist crack growth and failure under load. Notch sensitivity owing to cut-outs (e.g. windows), holes (e.g. fasteners) and changes in structural shape. Damage resistance against bird strike, maintenance accidents (e.g. dropped tools on aircraft), impact from runway debris, hail impact.
Environmental durability	Corrosion resistance. Oxidation resistance. Moisture absorption resistance. Wear and erosion resistance. Space environment (e.g. micrometeoroid impact, ionizing radiation).
Thermal properties	Thermally stable at high temperatures. High softening temperatures. Cryogenic properties. Low thermal expansion properties. Non/low flammability. Low-toxic smoke.
Electrical and magnetic properties	High electrical conductivity for lightning strikes. High radar (electromagnetic) transparency for radar domes. Radar absorbing properties for stealth military aircraft.

Table 2: Factors for the choice of structural materials for aerospace components. [1]

The specific characteristics of materials used for aeronautic components are shown in Figure 3, as mentioned before, depending on the function and charges applied for each specific component as well as the environment where it will be summited, a material specification for each component is defined, only materials that can handle and support these conditions is suitable for using it in these components.

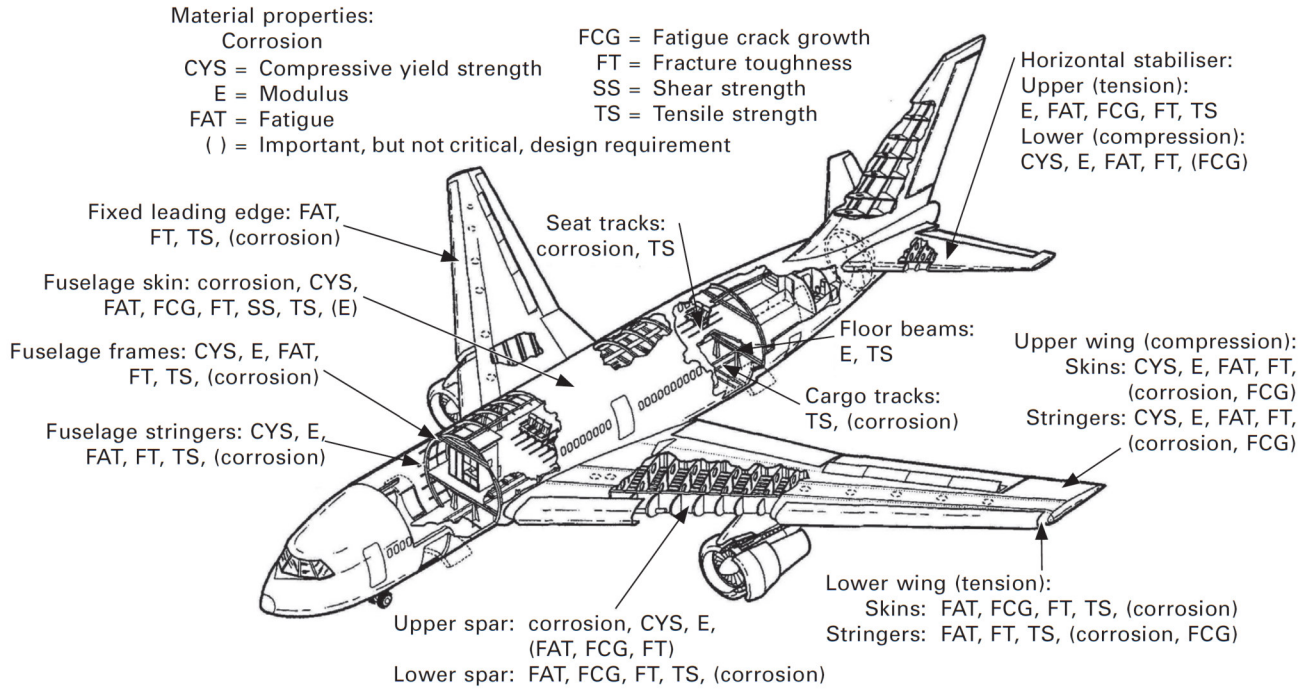


Figure 3: Material property requirements for the main aircraft structures. [1]

Aluminum Alloys

As seen in Figure 2, modern aircrafts are mainly composed of aluminum alloys accounting 60-80% of the airframe weight, this material is crucial for structural support in aircrafts and spacecrafts; this thesis work is dedicated to aeronautical aluminum alloys (7000 series with Zinc as main alloy) in rolled plates and machined to complex and thin structures, deeper analysis in this material will be reported. Aluminum, used since 1930's, covers most of the important characteristics demanded in aerospace applications, specially by its low density and high strength, allowing flights at high speed and high altitudes.

Over 400 000 tone of aluminum is yearly used for aerospace, the high percentage of aluminum in structural aerospace components is due to it's moderate cost, ease formability and machinability, low density, high specific stiffness and specific strength, high ductility, fracture toughness, resistance to fatigue and good control of properties by mechanical thermal treatments. Some of the disadvantages for aluminum are the excessive softening at high temperatures, sensible to stress corrosion cracking, difficulty to weld age-hardened alloys.

There are casting alloys and wrought alloys (heat-treatable and not-heat-treatable). Casting alloys are not used in aerospace structures, its mechanical properties are inferior to wrought alloys because are used in its cast condition, where not mechanical or heat treatment are implemented. Wrought heat-treatable alloys are widely used in aircraft structures, its strength properties can be enhanced by plastic deformation processes and heat treatments. The heat treatments are basically a thermal operation (increase and decrease of temperature) where metallurgical structure of the material is modified and consequently mechanical properties and internal residual stresses. Thermal treatments applied to wrought aluminum implies an increment of the strength by a process

called age hardening, also known as precipitation hardening.

Over 500 different aluminum alloys are classified by the International Alloy Designation System (IADS), this designation system is adopted by most countries. Table 3 shows the eight aluminum series where all aluminum alloys are allocated.

Alloy series	Main alloy element(s)	Heat treatable
1000	Commercially pure Al (> 99% Al)	Not aged-hardenable
2000	Copper	Age-hardenable
3000	Manganese	Not age-hardenable
4000	Silicon	Age-hardenable (if magnesium present)
5000	Magnesium	Not age-hardenable
6000	Magnesium and Silicon	Age-hardenable
7000	Zinc	Age-hardenable
8000	Other(including lithium)	Mostly age-hardenable

Table 3: Wrought aluminum alloy series. [1]

The main alloy element determines the series, the 8000 series is used for aluminum alloys that does not correspond to any other series where lithium is mainly used. Every aluminum alloy has an specific four-digit number, the first digit refers to the series, according to the main alloy into the aluminum; the second digit refers to the number of modifications sustained by the material, for example, 7250 Al, first digit (7) indicates that has Zinc as main alloy element and second digit (2) indicates that has been modified two times, nevertheless, it has similar composition to previous versions 7050 Al, 7150 Al. The two last digits only has meaning for 1000 series, where indicates the aluminum purity, for example 1000 Al (is at least 99.00%), 1065 Al (is at least 99.65%). For 2000 to 8000 aluminum series, the two last digits does not have relation with the alloy content, it only identifies the alloys into the series.

Temper designations for aluminum alloys	
F	As-fabricated (eg. hot-worked, forged, cast, etc.)
O	Annealed (wrought products only)
H	Cold-worked (strain hardened)
	H1x -cold worked only (x refers to amount of cold working and strengthening)
	H2x -cold worked and partially annealed
	H3x -cold worked and stabilized at a low temperature to prevent age-hardening
W	Solution-treated
T	Age-hardened
	T1 -cooled from fabrication temperature and naturally aged
	T2 -cooled from fabrication temperature, cold-worked and naturally aged
	T3 -solution treated, cold-worked and naturally aged
	T4 -solution treated and naturally aged
	T5 -cooled from fabrication temperature and artificially aged
	T6 -solution-treated and artificially aged
	T7 -solution-treated and stabilized by over-aging
	T8 -solution-treated, cold-worked and artificially aged
	T9 -solution-treated, artificially aged and cold-worked
	T10 -cooled from fabrication temperature, cold-worked and artificially aged

Table 4: Temper designations for aluminum alloys. [1]

To identify what temper has been applied to a material, a temper designation system defined by the American Standards Association is used. Forging treatment (hot or cold working) and thermal treatment (annealing, age-hardening) are considered as temper, usually used to improve metallurgical properties. Table 4 shows the letter designations for temper of aluminum alloys.

Focusing on aerospace applications, the series that can be strengthened by age hardening are the 2000, 6000, 7000 and many 8000 alloys. The age hardening process gives the strength needed to support high structural loads applied to the components of the aircrafts.

Many structural and semi-structural components are made of 2000 series aluminum, as seen in Table 3, the main alloy component is copper, which helps to form high strength precipitations during age-hardening heat treatment, it is mainly used in fuselage skins, lower wing panels and control surfaces due its failure resistance and toughness. Not all 2000 alloys are used in aeronautics, only few alloys are suitable for structural components. Table shows the used 2000 aluminum alloys and its mechanical properties.

Alloy	Temper	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
2017	T4	275	425	22
2018	T61	320	420	12
2024	T4	325	470	20
2024	T6	385	475	10
2024	T8	450	480	6
2025	T6	255	400	19
2048	T85	440	480	10
2117	T4	165	300	27
2124	T8	440	480	6

Table 5: Tensile properties of 2000 aluminum alloys used in aircraft. [1]

The main alloy element for 6000 series from Table are magnesium and silicon, it can be age-hardened with the formation of Mg_2Al_3 and Mg_2Si precipitates, these alloys are rarely used in aircraft structures due their low fracture toughness. 6061 Al is occasionally used in wing ribs, ducting, tanks, fairing and framework.

The 7000 series represents one of the most used series for aluminum in aerospace industry structural applications, as seen in Table the main alloy element is the zinc with some portion of copper, and in smaller portion magnesium; these alloys forms hig-strength precipitations [$CuAl_2$, Mg_2Al_3 , $Al_3Zn_2(Mg, Zn)_4$] during age-hardening process. 7000 series alloys are stronger than 2000 series, Table 6 shows the used 7000 series alloys in aerospace structures with the main alloys percentage compositions and Table 7 shows their tensile properties. Figure 4 shows the Aluminum alloys and tempers used in structural elements in the fuselage and wings.

Alloy	Cu	Zn	Mg	Mn	Cr(max)	Si(max)	Fe(max)
7049	1.2-1.9	7.2-8.2	2.0-2.9	0.2	0.22	0.25	0.35
7050	2.0-2.6	5.7-6.7	1.9-2.6	0.1	0.04	0.12	0.15
7075	1.2-2.0	5.1-6.1	2.1-2.9	0.3	0.28	0.4	0.5
7079	0.4-0.8	3.4-4.8	2.9-3.7	0.3	0.25	0.3	0.4
7090	0.6-1.3	7.3-8.7	2.0-3.0			0.12	0.15
7091	1.1-1.8	5.8-7.1	2.0-3.0			0.12	0.15
7178	1.6-2.4	6.3-7.3	2.4-3.1	0.3	0.35	0.4	0.5
7475	1.2-1.9	5.2-6.2	1.9-2.6	0.6	0.25	0.1	0.12

Table 6: Composition of 7000 alloys used in aircraft. [1]

Alloy	Temper	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
7049	T73	470	530	11
7050	T736	510	550	11
7075	T6	500	570	11
7075	T73	430	550	13
7075	T76	470	540	12
7079	T6	470	540	14
7090	T7E71	580	620	9
7091	T7E69	545	590	11
7178	T6	540	610	10
7475	T651	560	590	12

Table 7: Tensile properties of 7000 alloys used in aircraft. [1]

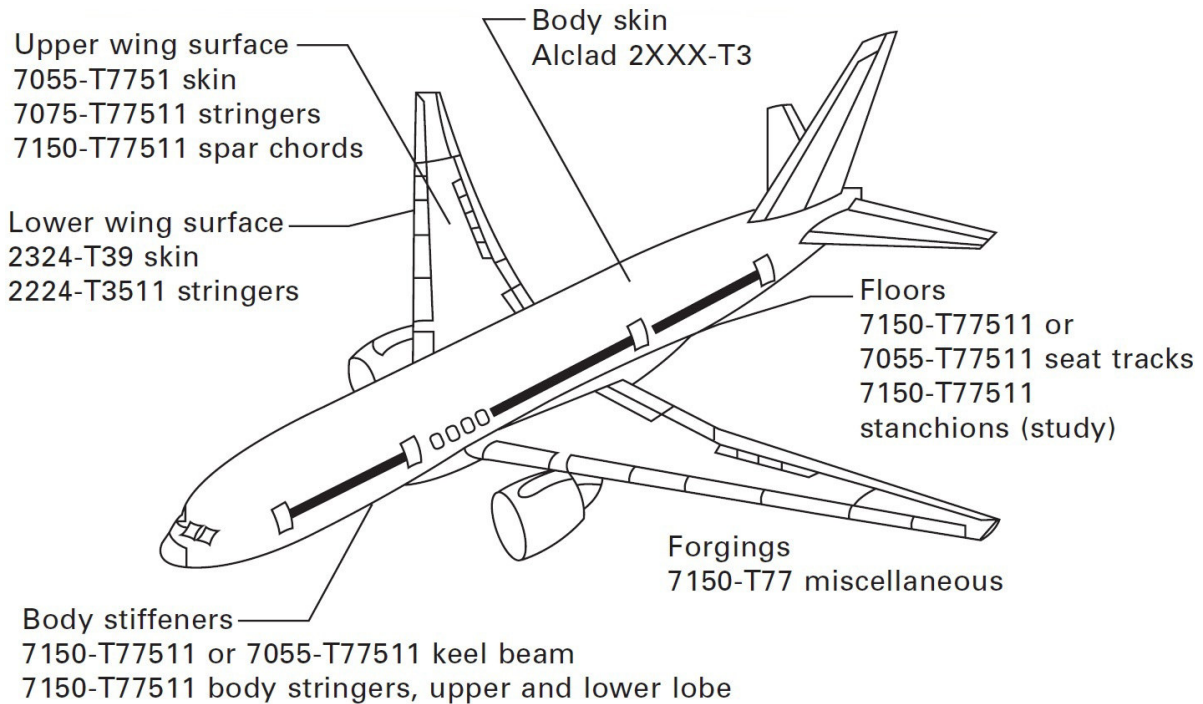


Figure 4: This figure shows the aluminum alloys and tempers used on the Boeing 777. [1]

Heat Treatment (Aging) of Aluminum Alloys

Only heat treatment age-hardenable aluminum alloys are used for aeronautic proposes, this process gives the high mechanical properties needed in structural parts. The age-hardening process consists in three stages, the solution treatment (dissolution of casting precipitates and dispersion of the alloying elements through the aluminum matrix), quenching (rapid cooling from high temperature to avoid formation of large, brittle precipitates) and artificial aging (reheating of the plate to a high temperature to allow the alloying elements to precipitate small particles that strength the alloy). This processes improve most important mechanical properties such yield strength ultimate strength, fracture toughness, fatigue endurance and hardness.

The solution treatment is the first stage in a heat treatment process, it is very important to dissolve any large precipitate after casting. These precipitates are formed during casting process and can importantly reduce mechanical resistance properties. The cooling rate after casting and alloying concentration can make these precipitates develop into coarse brittle particles which usually cracks in small plastic deformations. This stage consist into heating the aluminum to a temperature high enough to dissolve these precipitation without reaching the melting point; the dissolution ratio and solubility of alloys into material increase with temperature, a temperature just before melting point is desirable for this propose, it is very important to have a good control of temperature during the process in order to completely dissolve precipitates but without melt the metal.

After solution treatment, the piece is cooled rapidly to room temperature suppressing the reformation of coarse inter metallic precipitates and keep the alloying elements as a supersaturated solid solution in the aluminum matrix. This process occurs in few seconds, the high temperature piece is immersed into water to extract the internal thermal energy, a temperature gradient is developed into the piece where high temperature is at the center and decreases rapidly through thickness generating residual stresses; a way to reduce these residual stresses is to decrease heat flux introducing the piece into hot watter, making the temperature gradient less aggressive. The risk of decreasing the heat flux is that some precipitations can appear, this also reduces the possibility to strength by thermal aging. An optimal cooling heat flux is chosen in order to maximize the concentration of alloying elements dissolved into solid solution and minimizing at the same time residual stresses. Figure 5 shows the effect of cooling rate on yield strength in aluminum alloys used in aeronautics.

The last stage is aging, during this process occurs a transformation of the supersaturated solid solution into precipitate particles that can significantly enhance the strength properties. The process occurs naturally at room temperature, it can be also artificially performed increasing the temperature. The natural process is longer than the artificial aging process, its effects can be significant after many months or even years. Decreasing the temperature to -20°C significantly stops the aging process, in some cases postponing aging is necessary. Figure 6 shows the effects of natural aging into some aluminum alloys.

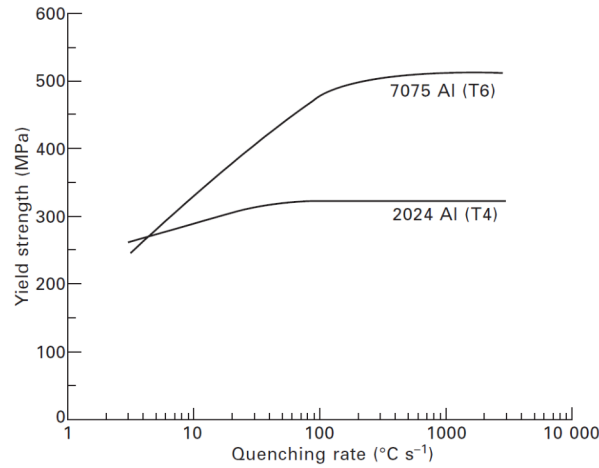


Figure 5: This figure shows the effect of average quenching rate on the final yield strength of aerospace alloys 2024 Al and 7075 Al. [1]

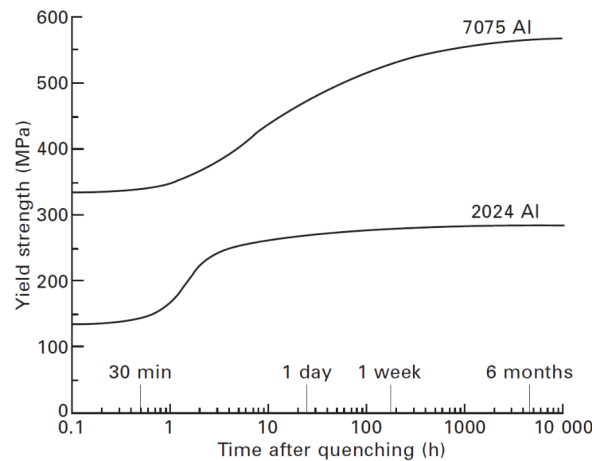


Figure 6: This figure shows the effect of natural aging time on the yield strength of 2024 Al and 7075 Al. [1]

When temperature is increased (150°C to 200°C) the aging process is speed up, the mechanical properties of the aluminum depends on the temperature and time of the operation. Figure 7 shows the typical effect of the temperature on the tensile strength of the aluminum alloy.

Titanium Alloys

Titanium alloys are considered as critical material for both structural and jet engine components in aerospace; the mechanical properties of these alloys are optimal for aerospace applications, due its moderate weight, high stiffness, high strength, resistance to fatigue, great corrosion resistance, and the capability to keep its mechanical properties in adverse conditions at high temperature. The most common titanium alloy is Ti-6Al-4V, its mechanical properties are better than mechanical properties of aluminum alloys, a drawback is that it is more expensive and heavy.

Titanium alloys are used in parts that need to support high loads in a small available space, some cases of applications are the landing gear and wing fuselage connections. As seen in Figure 2 titanium alloys represent 10% weight of commercial aircrafts and over 30% weight of military

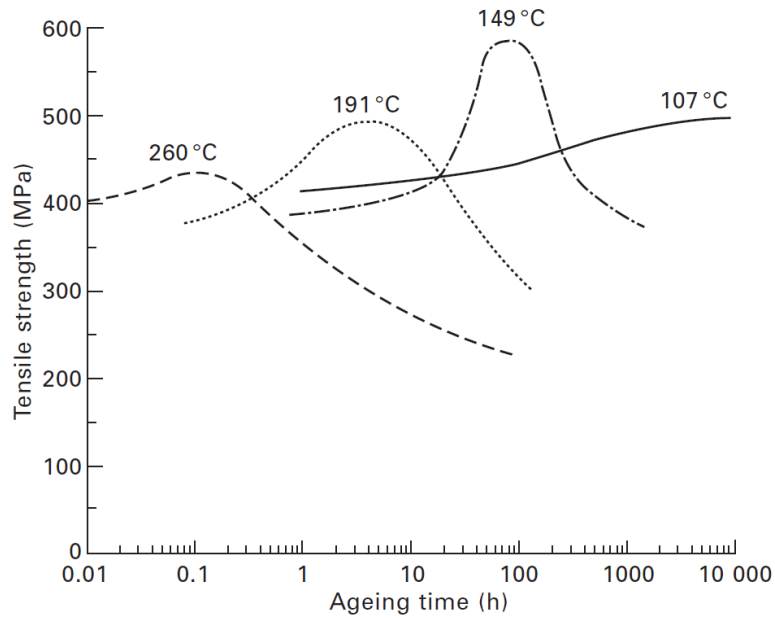


Figure 7: This figure shows the effect of aging temperature on the tensile strength of an aluminum alloy. [1]

aircrafts, this is because military aircrafts travel at higher velocity and need more resistance in structural components; titanium alloys are also widely used in engine jet parts, due their resistance stability at high temperatures (400°C-500°C) including fan blades, compressor parts, plug and nozzle assemblies in exhaust section.

Magnesium Alloys

Magnesium was one of the most popular metals used in aerospace structures due its very low density, it was widely used during 1940s-1950s but since then it was replaced by aluminum aged alloys and composites, nowadays magnesium is used in only 2% of helicopters structural components. The replacement of magnesium alloys by aluminum alloys and composites is mainly due its higher production costs and deficient resistance mechanical properties compared with these materials, it is also very susceptible to corrosion which means higher costs in maintenance and lower productive life, it is now only used in non-gas turbine engine parts, including gearboxes.

Steel

Despite steel is the most common material for structural mechanical components, in aeronautics its use represent only 10% of the aircrafts composition as seen in Figure 2; the resistant mechanical properties of steel used in aeronautics are about three times higher than aluminum alloys and two times higher than titanium alloys; it is used into the landing gear and wing box, where high loads are applied. The reason of its limited use in structural aircraft components is its high density, about three times heavier than aluminum and 50% heavier than titanium. It is also susceptible to corrosion and embrittlement producing cracking.

Nickel-Iron-Cobalt Superalloys

These materials are used in jet engine due its high resistance mechanical properties; these materials are mainly nickel, iron–nickel and cobalt alloys. The high temperatures does not considerably affect the mechanical properties of these materials, they are also persistent to corrosion and oxidation at the adverse conditions and high temperatures into the jet engines. Nickel superalloys are the most common, containing high concentration of chromium, iron, titanium, cobalt and some other alloying elements; these superalloys can operate at high temperatures (80°C-100°C) for long periods, ideal in jet engine components summited at these range of temperatures such high pressure turbine blades, discs, combustion chamber, afterburners and thrust reverser.

Composites

Composites material are gaining importance in aeronautic structural components, fiber-polymer composites are strong materials with very low density consisting in continuous fibers (carbon & glass) into a polymer matrix, mainly epoxy. The composites are lighter and stronger than aluminum alloys but more expensive and susceptible to damage by impacts. The main applications of fiber-polymer composites are in wings, fuselage, empennage and control surface. Fiber-metal laminates consist in a thin sheet of metal combined with fiber-polymer composites, this material is light, stronger, fatigue resistant than the metal components and higher resistance to impact than fiber-polymer composites. GLARE[®] is the most common fiber-metal laminate, consisting in layers of aluminum alloys with thin layers of fiberglass composite. Figure 8 shows a fiber-metal laminate and its components.

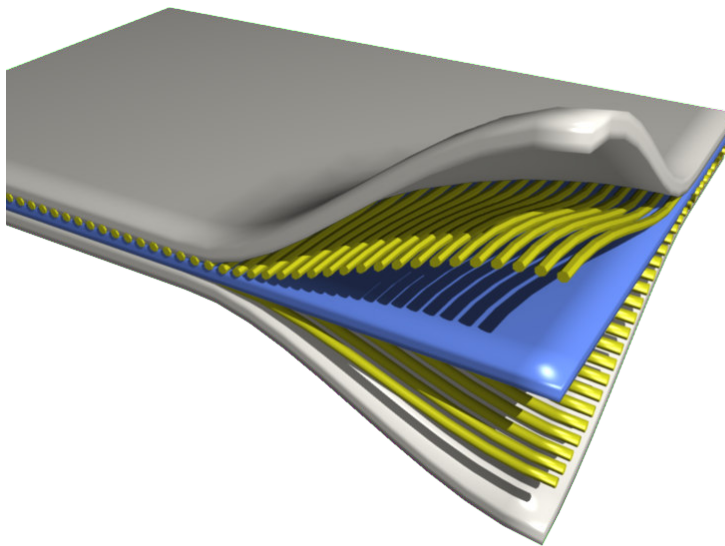


Figure 8: Fiber-metal Laminate; thin sheets of metal covered by fiber-polymer composite.

Aerospace Structural Components

Science of materials is very important for aerospace industry, nevertheless, for mechanical designing in aerospace, it is not enough to know the properties and behavior of materials, it is very important to know where this material will be implemented, the environment of the component is crucial for material selection (loads supported by the component, temperature, humidity, atmospheric pressure, etc.) the shape of the component will determine how the load is distributed, and where the stresses will be concentrated, the temperature will modify the mechanical properties of the material, in addition with temperature, the humidity will determine the oxidation and corrosion rate. A material that can satisfactorily handle this environment is chosen for the component.

Some structural components are crucial for the success of aircraft design, these components supports high loads and the correct geometry and material guarantee the safety and correct functionality of the aircraft, some critical structures are the fuselage, wings, landing gear and empennage; for engine critical components for safety are the turbine blades and discs. A failure in any of these components is translated to critic stability and safety of the aircraft.

Materials used in aerospace must have a complex combination of properties (high stiffness, strength, fracture toughness, fatigue endurance and corrosion resistance) supporting complex loads in repose, departure, flight and landing. These structures must support these complex loads while being inexpensive and easy to produce. These structures must last during the life cycle of the aircraft (25-30 years for commercial aircrafts & 15-40 years for flight aircrafts) resisting to crack, corrosion, oxidation or any other damage manifestation.

Another important designing factor is the density of the materials, the structural components account for the 20-40% of the aircraft weight, any reduction in mass for the structural components increases the payload capacity, decreases the fuel required, higher range-speed and smaller engine jets. Table 8 shows the percentage in weight of the main structural components, Figure 9 shows the weight percentage of every aspect for a commercial aircraft.

Structural Component	Sailplane	Light and executive aircraft	Subsonic airliner	Military fighter
Fuselage	25	11	7	12
Wing	30	14	8	12
Stabilisers	3	2	4	4
Undercarriage	2	4	4	4
Total %	60	31	23	32

Table 8: Breakdown of structural weight for various aircraft types as a percentage of total weight. [1]

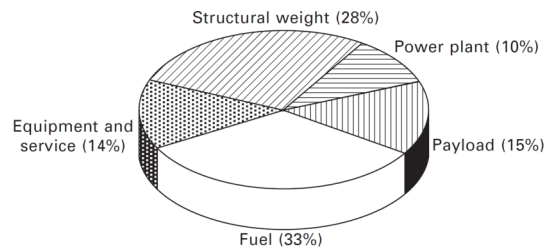


Figure 9: Approximate breakdown of take-off weight of large passenger aircraft. [1]

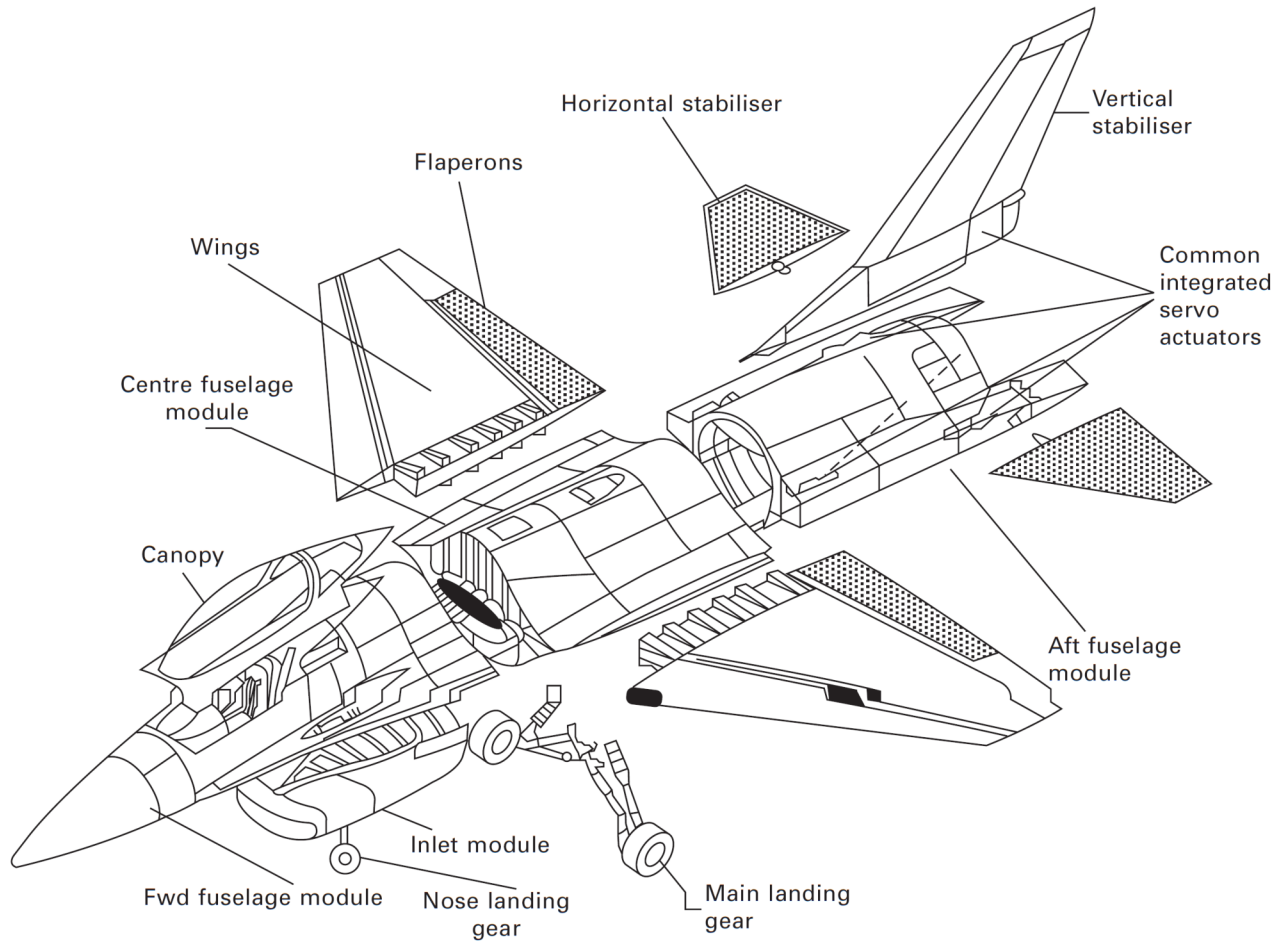


Figure 10: Main structural components of a modern military aircraft. [1]

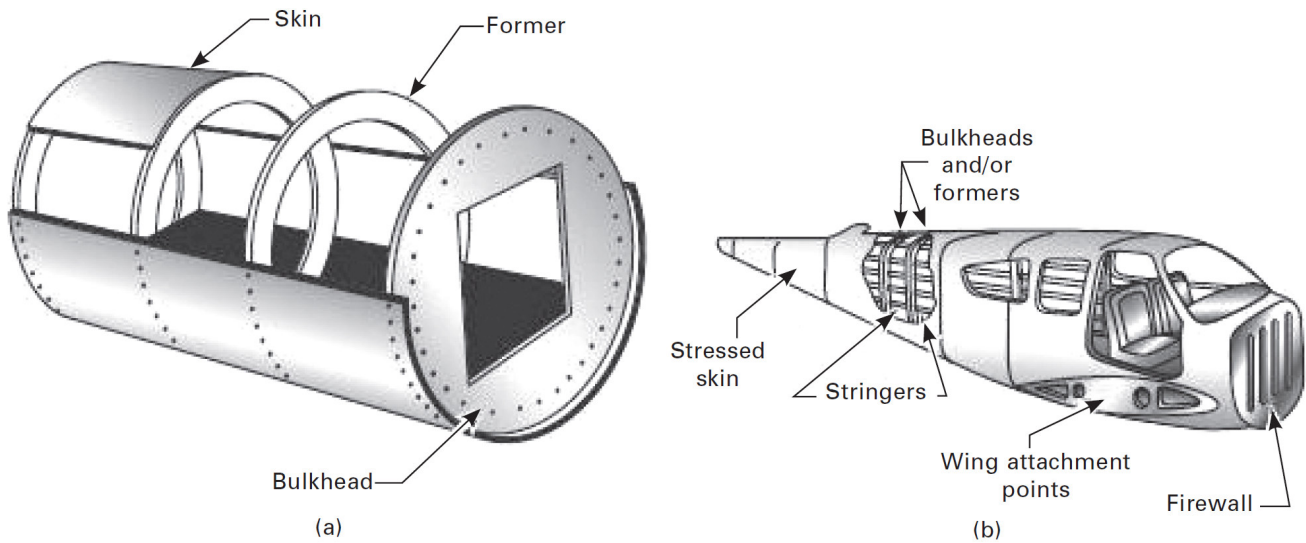


Figure 11: Examples of (a) monocoque and (b) semimonocoque fuselage structures. [1]

Figure 10 shows the main structural components of a modern military aircraft, composed by a fuselage, wings, empennage, landing gear and control surfaces such as flaps, elevators and ailerons. These elements must be light and strong, as a result of the combination and optimized design and high-performance materials. A monocoque is an unreinforced shell, thick enough to avoid bucking under operation. A semimonocoque structure consists of a thin shell reinforced by stiffeners to support operational loads without bucking. Figure 11 shows both type of fuselages, monocoque and semimonocoque.

The structural components of an aircraft supports ground loads (aircraft operation at ground such landing, taxiing and departure) and flight loads (loads during flight), these loads can be surface loads (aerodynamic and hydrostatic pressures over the skin) and body loads (acting over the volume of the structure produced by gravitational and inertial forces), all these loads produce tensional, compressional, bending, shear, torsion and any combination of stresses over the components. The complex structural design of an aircraft deals with all these combination of charges, optimizing the weight of the total structure, choosing the correct material and shape of the components, Figure 12 shows these structural components into a modern aircraft.

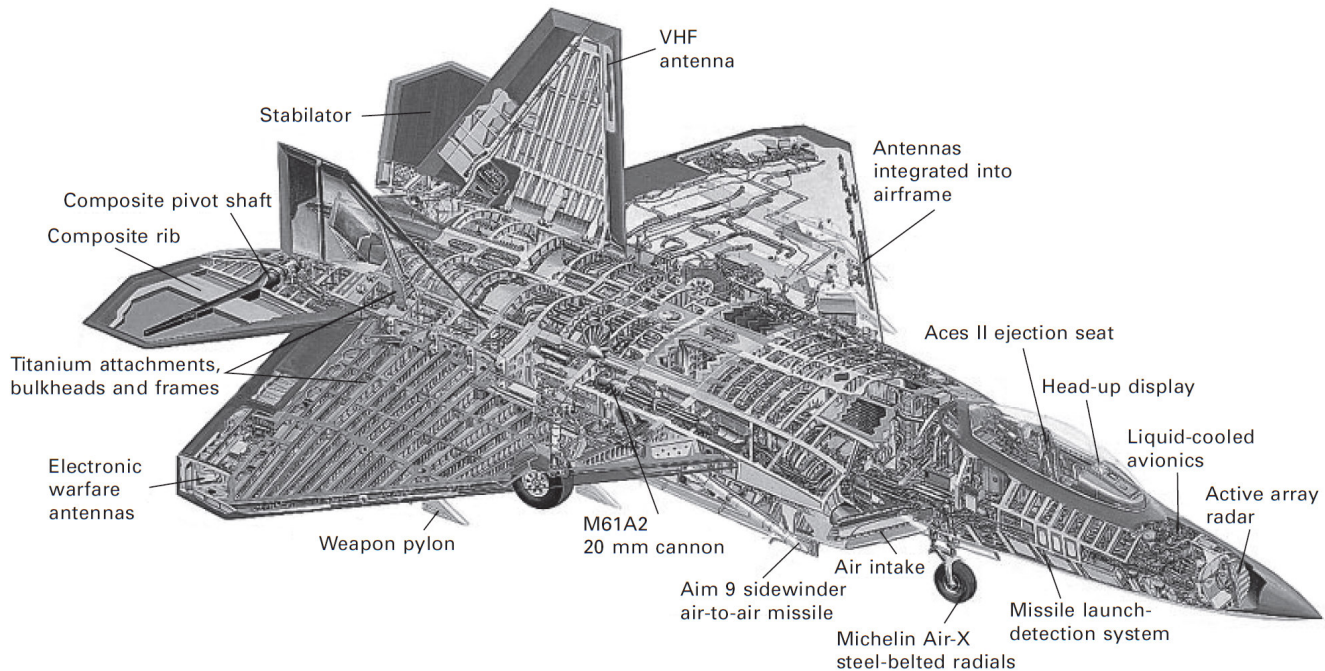


Figure 12: Internal structural design of a modern aircraft. [1]

The wings are another critical structural component in an aircraft, they support flight loads and transmit them to the fuselage by the wing box and connections. It also supports the engine jet mass in cantilever, this mass is over 10% of the total mass of the aircraft as seen in Figure 9. The structural composition of the wings is basically thin skins supported by structural ribs, stringers and spars. This structural arrangement supports bending, tension and compression loads; when the aircraft is on ground, the wing bends (tension in the upper surface, tension in the lower surface); when the aircraft is flying, the wing is bent (compression in the upper surface, tension in the lower surface) by pressure difference and distributed lift loads, Figure 13 shows this bending load on wings.

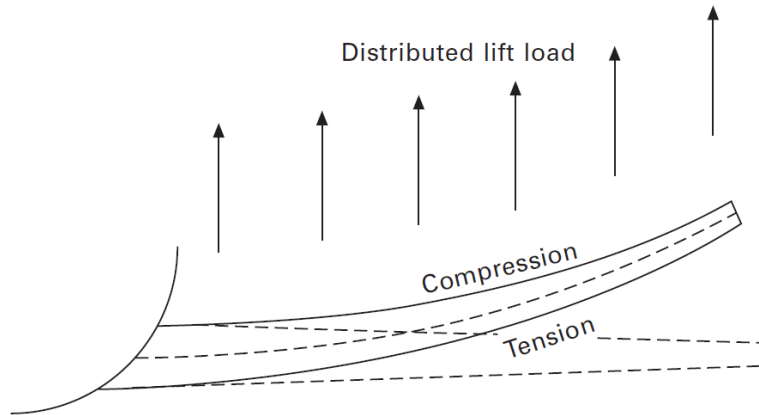


Figure 13: Bending action of an aircraft wing during flight. [1]

The empennage and control surfaces are part of the tail of the aircraft at the end of the fuselage, this system controls and stabilizes the direction of the aircraft, Figure 14 shows the basic elements of this control system. The empennage consists of the tail assembly (vertical stabilizer, horizontal stabilizers, rudder, elevators and the rear section of the fuselage). The stabilizers provide stability for the aircraft to keep its straight path; the horizontal stabilizers prevent the up-and-down, or pitching, motion of the aircraft nose. The rudder is used to control yaw, a side-to-side movement of the nose. The elevator is the moving section at the rear of the horizontal stabilizer, used to generate and control the pitching motion.

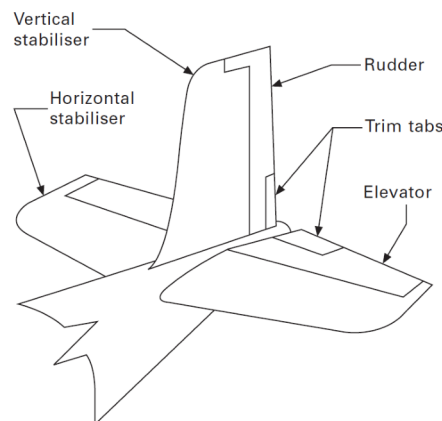


Figure 14: Typical empennage layout. [1]

The landing gear is a complex system of structural components, hydraulics, energy absorption components, brakes, wheels and tires. This system support the high landing loads and stop the landing gear from collapsing under the aircraft weight. Figure 15 shows the the elements of the landing gear system.

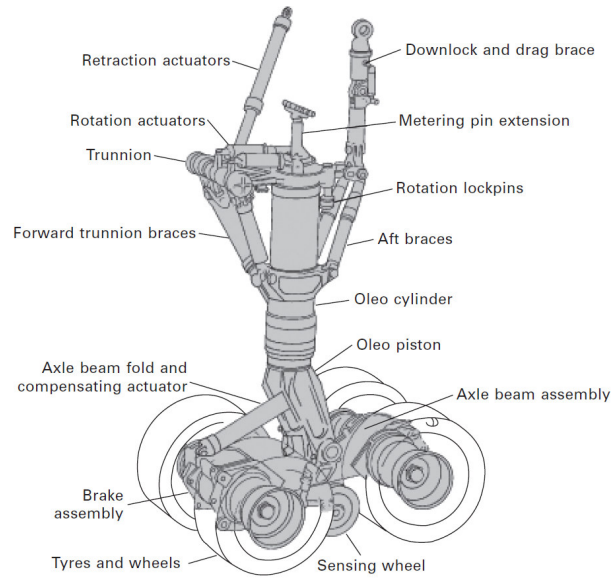


Figure 15: Main-wheel bogie. [1]

Figure 16 shows the structural components of a helicopter, the airframe is summited to high loads at two zones, the connection to the tail boom and the connection to the main rotor drive shaft or turbine engine. Torsion and bending loads are applied by the tail boom during flight, high tension and shear forces occur around the drive shaft connection. The rotor has a mast, hub and blades, it is classified depending on the blades configuration and relative to the hub movement (rigid, semirigid and fully articulated). The mask is a cylindrical shaft which extends upwards from, driven by the transmission.

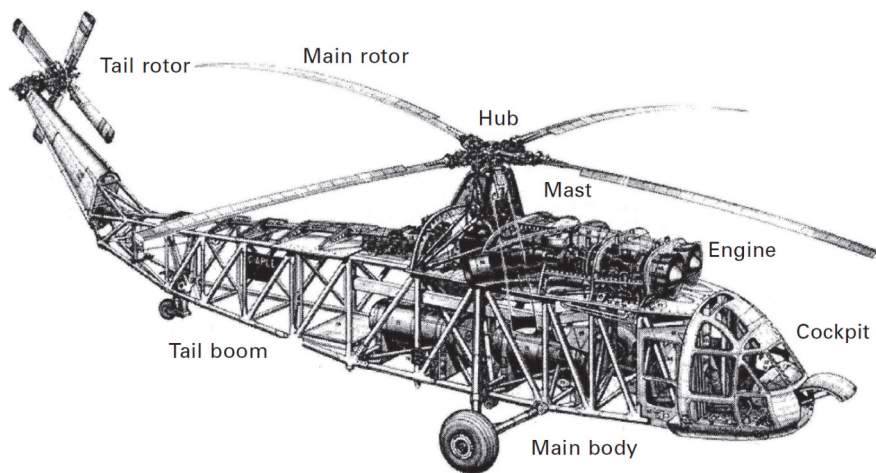


Figure 16: Structural design of a typical helicopter. [1]

Aerospace structures are more complex, an space shuttle consists of an external fuel tank, two solid rocket boosters and the Space Transportation System (STS) orbiter vehicle. Figure 17 shows the main components of the orbiter, it seems like a conventional aircraft, using most of the same materials. This structural system have some specific materials that conventional aircrafts does not have, the shuttle supports very high temperatures when passing trough the earth atmosphere and re-entry (600°C - 700°C).

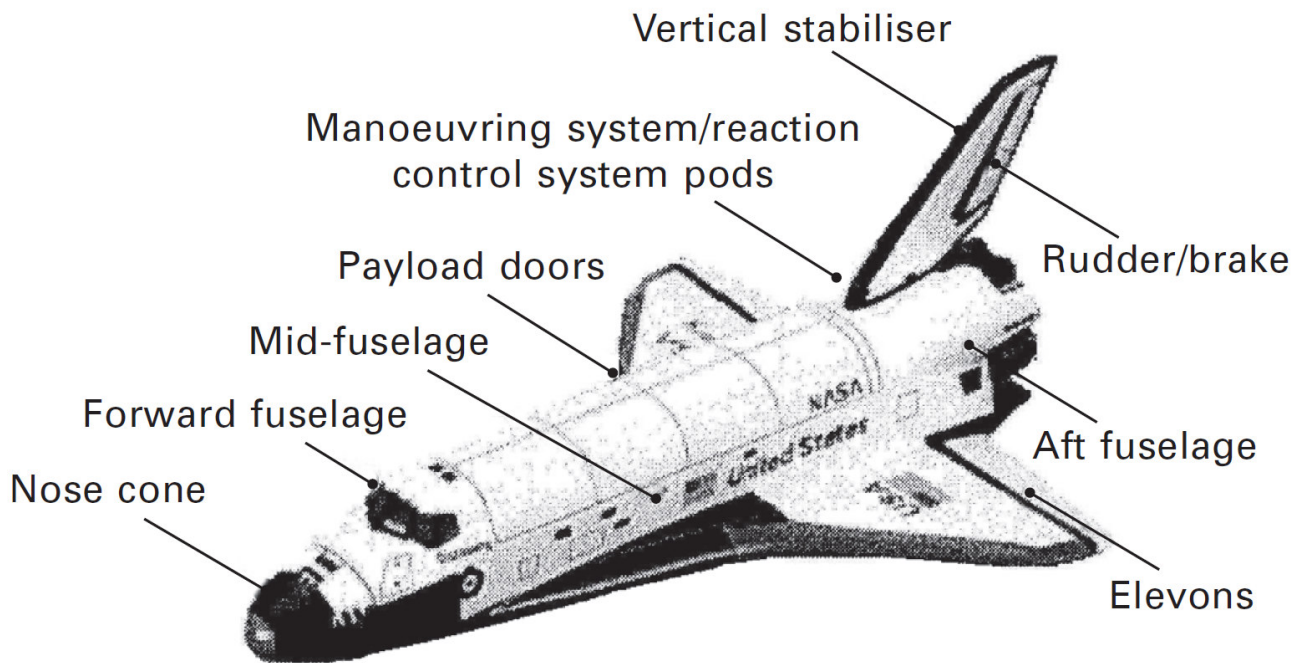


Figure 17: Main sections in the space shuttle orbiter. [1]

Manufacturing Processes for Structural Components

A high percentage of structural components in aerospace come from rolled plates which are treated with forming and machining manufacturing processes. It is important to know the characteristics of the processes involved into the fabrication of rolled plates where the mechanical properties and micro structure of the metal is determined by each of these processes. Aluminum is analyzed as it is the most used material in aerospace structural components; a full description of the processes involved in the production of aluminum rolled plates is developed. Machining is also explored as one of the most important manufacturing processes to define the complex shapes of structural components in aerospace.

Aluminum Rolled Plate

As explored in previous sections, aluminum alloys are widely used in aeronautics by its good physical and mechanical properties balance (lightweight, strength, ductility, joinability, reflectivity, heat conductivity, electrical conductivity, corrosion resistance, non toxic, non combustible, recyclable); aluminum plates can be formed into regular thickness structural parts, they can be also machined into complex shape structural components which can be welded into large, strong and durable parts. Some other uses for aluminum plates are railroad gondola and tank cars, battle armor for military tanks and vehicles, tanks for storing and transporting cold liquefied natural gas, aircraft structural parts and spacecraft components.

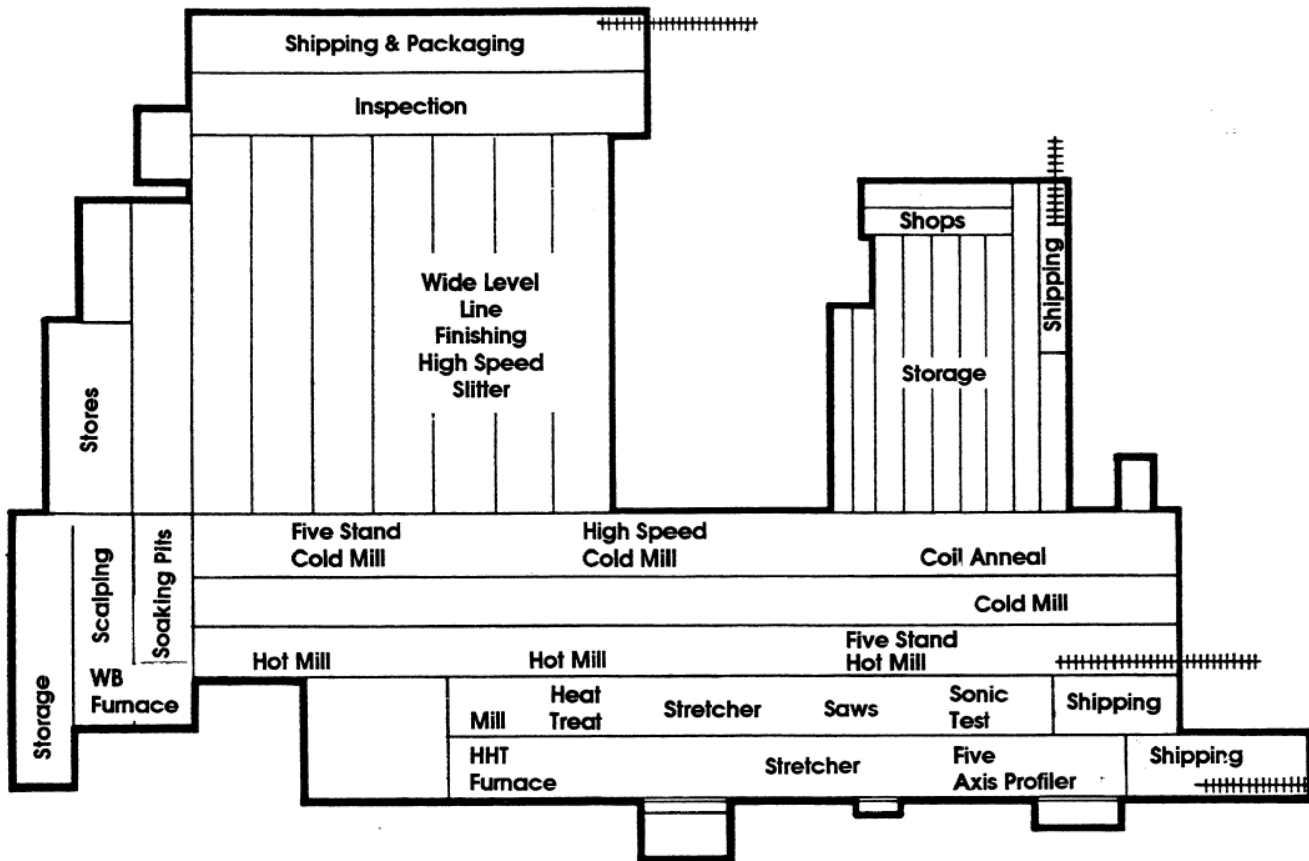


Figure 18: Floor plant, typical aluminum rolling plant. [2]

Aluminum was discovered in 1807, and was isolated the first time in 1825, limited produced in 1845, widely produced after the invention of Hall-Heroult production process in 1886. It is now the second most used metal in the world after iron. Metal rolling was initially practiced on beginning of the 16th century then adapted to aluminum. By 1903 over 3 million kg of aluminum was produced annually, one third was into sheet shape. The application of aluminum into thin skins in aeronautics appeared on 1917. Figure 18 shows a typical rolling plant, technology as been applied to the rolling process with time, having faster machines at higher quality and safe operational conditions.

Mineral Extraction

Aluminum is the third most common element in a ten miles depth of solid crust portion of earth. Figure 19 show this crust portion composition with oxygen 47%, silicon 28% and aluminum representing 8%, others includes 2.1% magnesium, 2.6% potassium, 2.8% sodium, 3.6% calcium, 5% iron and 0.14% titanium, manganese, nickel copper, zinc and lead.

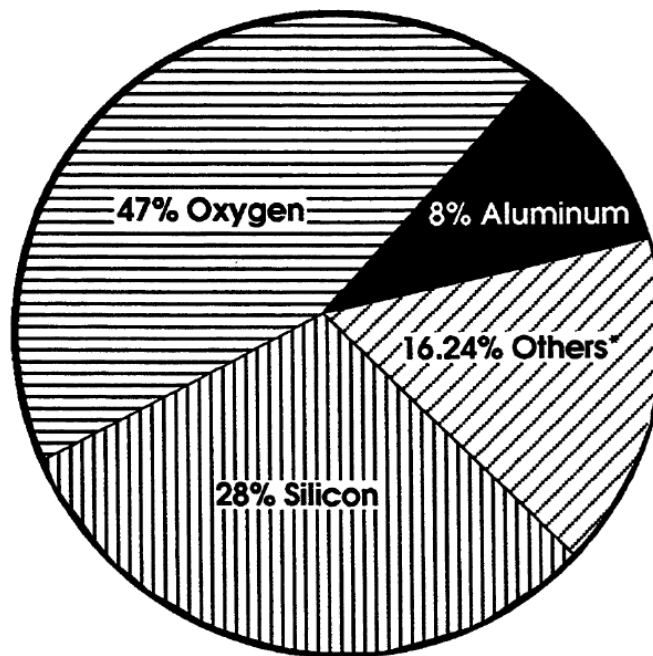


Figure 19: Main elements found in the earth's crust. [2]

Bauxite is the ore where most aluminum is produced, containing 40-60% impure hydrated aluminum oxide, containing also iron oxide, silicon oxide, titanium oxide and water. Tropical and subtropical areas are the richest in bauxite ores, often found close to the earth's surface, it is estimated that bauxite worldwide reserves could last 300 to 500 years. The basic mining extraction methods consist in open pits by conventional digging machinery, the bauxite is then crushed, washed and dried in preparation for separation of the alumina from the other undesirable components.

Refining of aluminum from bauxite is done by the Bayer process; caustic soda is used at high temperature and under steam pressure to digest the crushed, washed and dried bauxite, this dissolve the aluminum in a mixture with undissolved impurities called red mud. The red mud is

removed by filtration, then is transferred to tall tanks called precipitators. In the precipitator tank, the hot solution is cooled by aluminum hydroxide to simulate the precipitation of solid crystals of aluminum hydroxide and sodium hydroxide, the aluminum hydroxide settles to the bottom and it is removed from the tank. The aluminum hydroxide is washed, removing residues of caustic soda and posteriorly heated to drive excess of water in long rotating kilns called calciners. Alumina emerges as a fine white powder, refined alumina consists of about equal weights of aluminum and oxygen, which must be separated to produce aluminum metal.

The bond between aluminum and oxygen is very strong, it is necessary a huge amount energy to separate them by heating, aluminum oxide melts at 2015°C , while pure aluminum melts at 660°C . The first alternative to heat separation were the chemical methods developed in the mid of 19th century; these methods were very expensive which increases the value of aluminum, using the small amounts of aluminum produced for jewelry. An alternative for chemical methods, electrical methods were developed, at that time the low electrical resources were not enough to supply the high energy needed for separation of aluminum from oxide, adding the insolubility of alumina in water.

The dynamo arrived in 1886, generating the enough amount of energy to separate aluminum from oxygen; on 1886 Charles Martin Hall in the United States and Paul L.T. Heroult in France discovered simultaneously that alumina dissolve in a molten mineral called cryolite at about 950°C , in solution, the aluminum oxide can easily be decomposed into aluminum and oxygen by an electric current. This separation process needs a lot o electricity but in few volts, it is easy to connect many cells in series along the electrical circuit, currents of around 250,000 amperes are used nowadays with only four or five volts, using six or seven kilowatts per pound of aluminum produced. The electrical resistance produces heat enough to keep the solution molten, the separated oxygen atoms carry a negative electrical charge being attracted to the positive poles in each cell. These poles are made of carbon forming carbon dioxide and carbon monoxide when combining with oxygen. The gases formed leave the melt in form of bubbles, resting aluminum at the bottom of the cell. This process consumes the carbon anodes, which must be replaced or continuously fed. Once melted aluminum is sufficient collected at the bottom of the cell, it is siphoned into a crucible for transport to alloying and casting facilities, the aluminum obtained into this process is more than 99% pure. Figure 20 shows the main steps in the Bayer alumina refining process and the Half-Heroult aluminum reduction process.

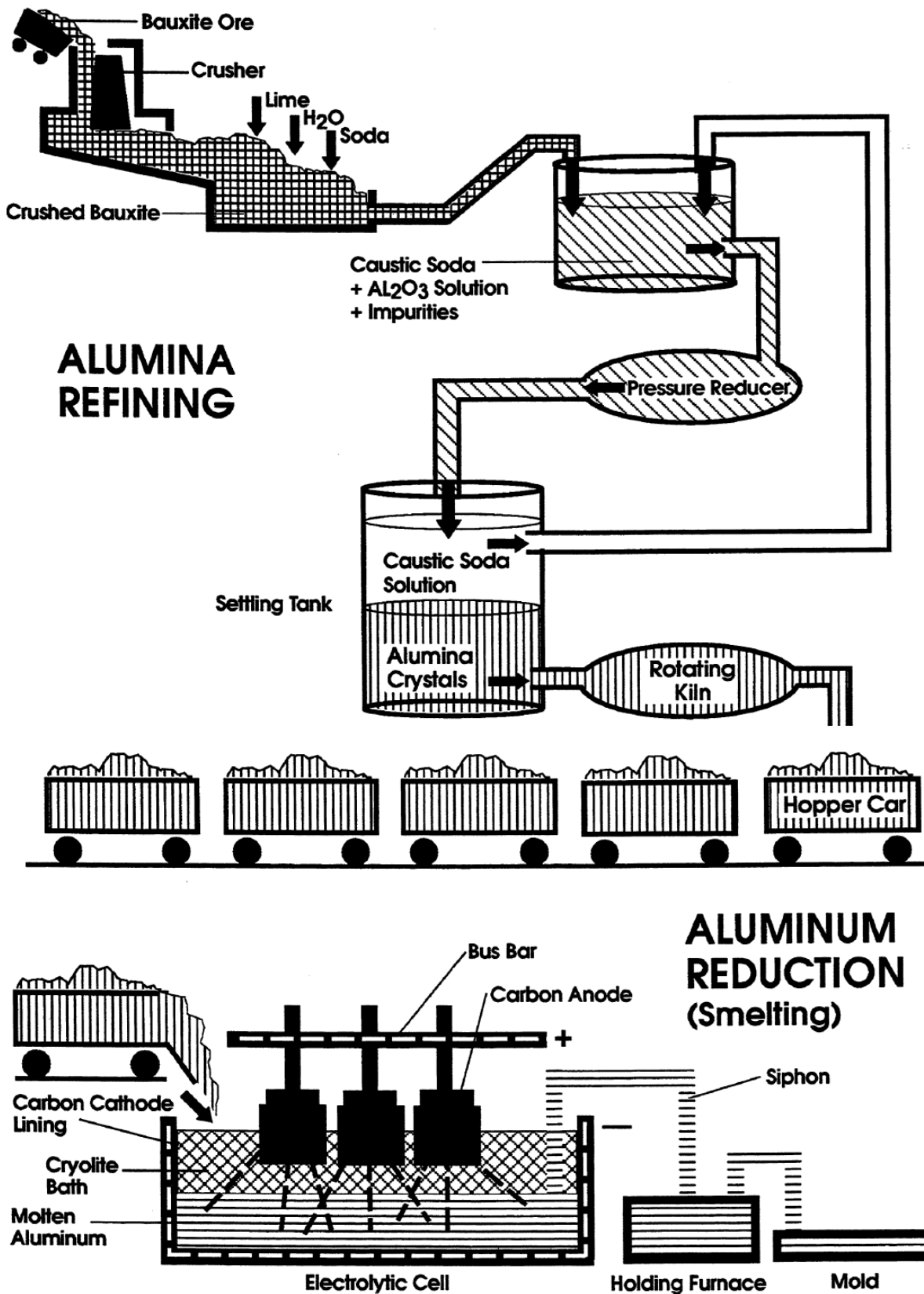


Figure 20: Main steps in the Bayer alumina-refining process and the Hall-Heroult aluminum-reduction process. [2]

Metal Cleaning

When material is charged into the alloying furnace, it carries some unavoidable foreign elements and non-metallic materials can be produced by chemical reactions, causing post processing problems, imperfections and bad quality of the material in general. This undesirable foreign matter is hence removed from the alloys by fluxing and filtration processes.

Fluxing is needed to remove dissolved hydrogen gas from molten aluminum through bubble gas, sweeping some solid impurities to the surface in form of frothy dross that is posteriorly removed. Airborne water vapor, materials added to the melt or furnace walls, tools or anything else that comes in contact with the melt generate hydrogen gas that dissolves easily into the molten aluminum. This hydrogen dissolved into the melt is removed with bubbling dry, inert hydrogen-free gases (generally nitrogen) through the aluminum, diffusing into these bubbles the previously diffused hydrogen into the melt, carrying it out of the melt by the rising bubbles. The inert gas used for this propose may be mixed with small amounts of chlorine or other reactive gases in order to react with some specific impurities of the aluminum such as sodium, calcium or lithium, removed posteriorly by filtration. The process consists in porous plugs situated at the bottom of the furnace, spinning rotors and fluxing wands, producing uniform distribution of bubbles enhancing diffusion and chemical reaction through all the material.

A complementary process is needed to clear any foreign particles or inclusions not removed in fluxing or posteriorly developed. Filtration is applied to the molten aluminum before it is cast into rolling ingot, it is sometimes combined with fluxing process, removing potentially harmful particles or inclusions that may weaken the final product. This process uses deep bed filters used for multiple casts, it consist on 125-380mm thick layers of media (sintered high density alumina flakes or spheres with 6-19mm diameter); The molten aluminum is passed through these layers which encapsulates and retains these undesirable particles. Some other filters are used, improving the method and quality of molten aluminum, but the bases are the same.

Casting

To prevent cracking during solidification or for grain refinement, some additives in small amounts are used into the molten aluminum; titanium is generally used for this propose in addition with boron or carbon, creating numerous nucleation points, where solidification begins during cooling of the ingot. This additives disperses stresses throughout the ingot when solidification occurs, reducing cracking for high levels of residual stresses. The molten aluminum is poured through a trough into the ingot-casting mold, the additive for grain refining is added before casting at the last minute because it is more effective than if it is longer in contact with the molten aluminum.

Continuous Casting

In continuous casting processes, molten material is solidified into a continuous strip, the methods used for metal solidification are roll casters, belt casters and block casters. Sheet is taken from molten metal, solidified and coiled in one operation in these methods. Main differences between continuous casting and DC ingot casting are the reduced hot working in continuous casting compared with DC ingot casting, the non homogenization between casting and hot rolling and non scalping between casting and hot rolling. The lower hot working in continuous casting is a result

of the reduced casting thickness seen in continuous casting. This smaller thickness in continuous casting, the strip cools and solidifies faster, it is partly pre-homogenized to avoid supersaturation of alloying elements. Different metallurgical structures even in similar alloys are the result of lack of homogenization and reduced hot working; continuously cast alloys might have different capabilities than DC ingot casting.

Strip Casters

The resultant continuous sheet is coiled immediately after casting without additional rolling, this is possible due its small thickness. Posterior rolling process may be applied to reduce thickness of the sheet, alternatively, the cast sheet can be hot rolled by a mill to reduce the thickness before coiling.

Roll Casters

The molten aluminum flows between a pair of water-cooled rolls, when molten aluminum touch the rolls it solidifies at a range of heat flux between $55\text{-}555\frac{\text{°C}}{\text{s}}$, having some hot deformation when passing through the rolls. Roll casters are able to produce continuous sheet in the range of 760-2030 mm wide, at $2\text{-}3\frac{\text{m}}{\text{min}}$, producing 10-18kg per hour per cm of width.

Slab Casters

Slab casters produce continuous aluminum plates without any hot deformation in the caster. The plates emerge with as-cast metallurgical characteristics and must be rolled by hot mill to achieve wrought aluminum properties and a sheet gauge than can be coiled. The typical production is between 225-2030mm wide at a linear speed of $6\frac{\text{m}}{\text{min}}$, at a range of 180-225 kg per hour per cm of width. The solidification rates at slab casters are around $0.5\text{-}5\frac{\text{°C}}{\text{s}}$, solid slab emerges at a temperature of 540°C , not requiring preheating for hot rolling, the most commercial types of slab casters are belt and block casters.

Belt Casters

Molten aluminum flows between two almost horizontal, continuous, thin metal belts that are in constant motion, the metal side dams moving with the belts containing the aluminum while it solidifies, this belt is usually inclined 5 to 9 degrees minimizing turbulence in the pool of molten aluminum; belt speed is synchronized with the metal flow rate. The heat from metal is transfered through films of lubricant to the metal belts, which are cooled with water on their external side, producing 12-25mm thick slabs. It is then rolled at low speed reducing the slab to coils of thinner sheet stock for eventual re-rolling. Figure 21 shows the belt caster process.

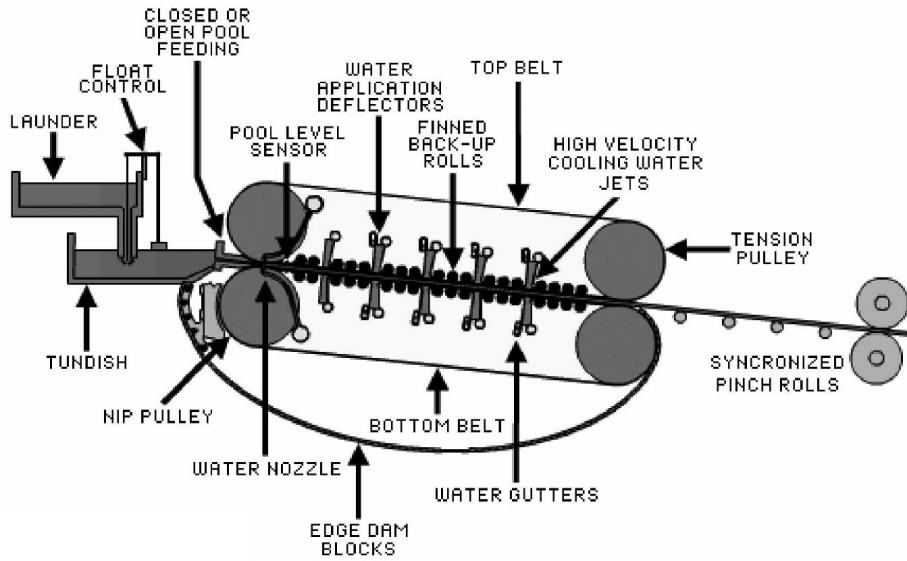


Figure 21: Belt slab caster process description. [2]

Block Casters

Block caster has the same principle as the belt caster; aluminum slab is shaped between upper and lower walls, these walls consist of thick blocks of metal lined up side-by-side. The sides of the blocks away from the aluminum are attached to a jointed loop belt, as this loop belt rotates around its drive gears, each block takes its turn lining up with its neighbors to make contact with the molten aluminum from the nozzle. The blocks absorb the heat from the molten aluminum solidifying it, when the blocks move around leaving the aluminum, a cooling system cools down the hot blocks before they touch again the molten metal. It is usually hot rolled after block casting to reduce the thickness. Figure 22 shows the block caster process.

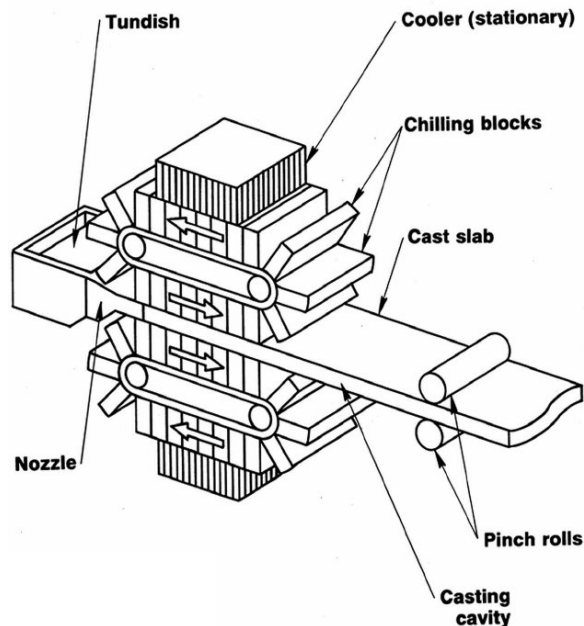


Figure 22: Block slab caster process description. [2]

DC Ingot Casting

Molten aluminum alloys is stored before casting in a holding hearth at a temperature range of 700-730°C, the temperature decreases by about 22-28°C upon transfer to the casting station. Direct-chill ingot casting takes place in a DC casting pit, each casting of ingot is called a drop. DC molds are typically 40-70 mm thick per 1.1-2 m wide. The molds are water cooled to increase the solidification speed of the ingot, the ingot decreases the temperature to 300-500°C contracting while cooling, separating with the mold walls before it emerges. Figure 23 shows the schematic representation of the direct-chill ingot casting process.

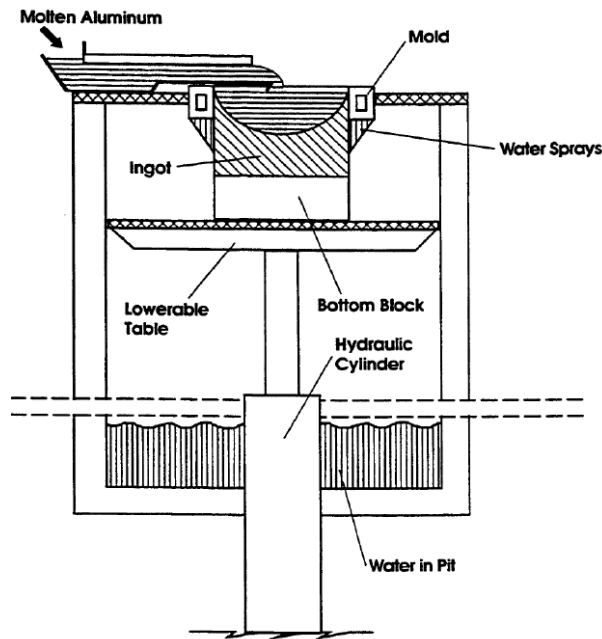


Figure 23: Direct-chill ingot casting (schematic). [2]

At 50 mm/min, it takes about 2-1/2 hours to cast a 7365 mm long ingot. DC casting has been used to produce ingots as much as 11.25 m long or longer. Removal heat rate is very important to avoid undesirable residual stress trough the ingot, a temperature gradient is developed by the heat extraction at the surfaces of the ingot, having higher temperatures at the center and lower temperatures at the edges. Figure 24 shows the temperature gradients in an idealized case, an average casting speed and slow casting speed.

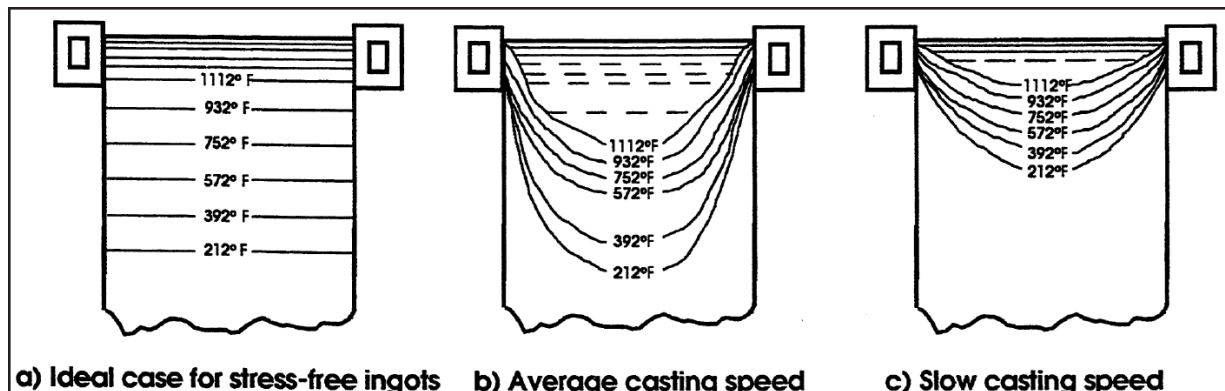


Figure 24: Temperature distribution in an ingot during direct-chill casting. [2]

Electromagnetic Casting

A variation of the DC ingot casting is the electromagnetic casting (EMC), in this process, a magnetic field confines the molten aluminum while its shell initially solidifies; the need of scalping is reduced by the continuous cooling and elimination of the liquated zone. There is not contact between the aluminum and mold walls, avoiding surface enrichment of alloying elements, producing ingots with smoother, metallurgically more homogeneous surfaces that need small or does not need scalping or edge trimming.

Surface Scalping

After casting, some irregularities or excess concentration of oxides or alloying elements are found at the surfaces of the ingots; scalping is needed to remove all these defects and undesirable concentration of alloying elements, providing smooth, metallurgically homogeneous surfaces, promoting high quality rolling process. The process consist in a milling machine with a horizontal mill spanning about 1.5 m or more and rotating on a vertical axis, the scalper mills the rolling face of the ingot, milling one side and turning the ingot over to scalp the other side. The edges and the end are trimmed and do not need scalping.

Rolling

The rolling process shape the sheet with accurate dimensions, with some other attributes as flatness, edge quality and regular thickness with null or small superficial defects. This process basically consist on two cylinders which draw aluminum through, reducing its thickness to the width of the gap between them.

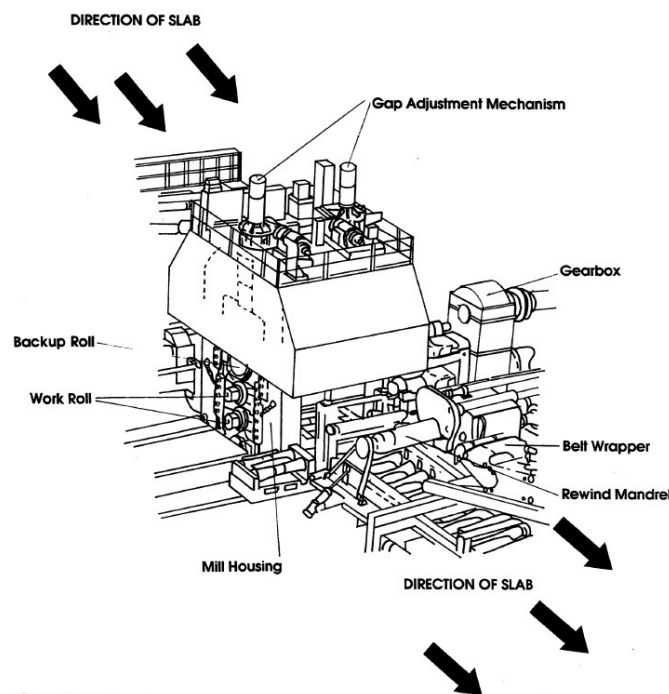


Figure 25: Main features of a four-high rolling mill. [2]

The components shown in Figure 25 are basically the mill stand (the frame structure supporting the components of the machine), back-up rolls (support the work rolls against excessive flexing and vibration), Drive motors (provide the power needed to feed the sheet and shape it), gearboxes (convert rotation rates of the motor in appropriate rates and torque for deformation), drive spindles (transmit the turning force of the motors to the cylinders), roll bending machinery (induce slight, controlled flexing in the rolls to compensate the thermal expansion or distortion, controlling the flatness of the sheet), gap adjustment machinery (set the gap between work rolls accurately and maintain it against the resistance of the alloy undergoing thickness reduction), coolant system (apply coolant liquid to the rolls).

The most important components of the mill are the work rolls, which are in contact with the aluminum sheet and transfer the mechanical energy to shape it with smaller thickness; the surface finish of the sheet strongly depends on the mechanical properties of the rolls, producing from rough to mirror-smooth finish surface sheets. The mechanical properties of the rolls includes hardness and high stiffness complemented with the diameter of the rolls which determine the quality of the sheet. A typical challenge in rolling is the roll bending due the high charges involved in sheet deformation, high stiffness in rolls is needed, an arrangement of several rolls supports the work rolls to avoid blending when rolling. Figure 27 shows the typical configurations for different sheet quality requirements.

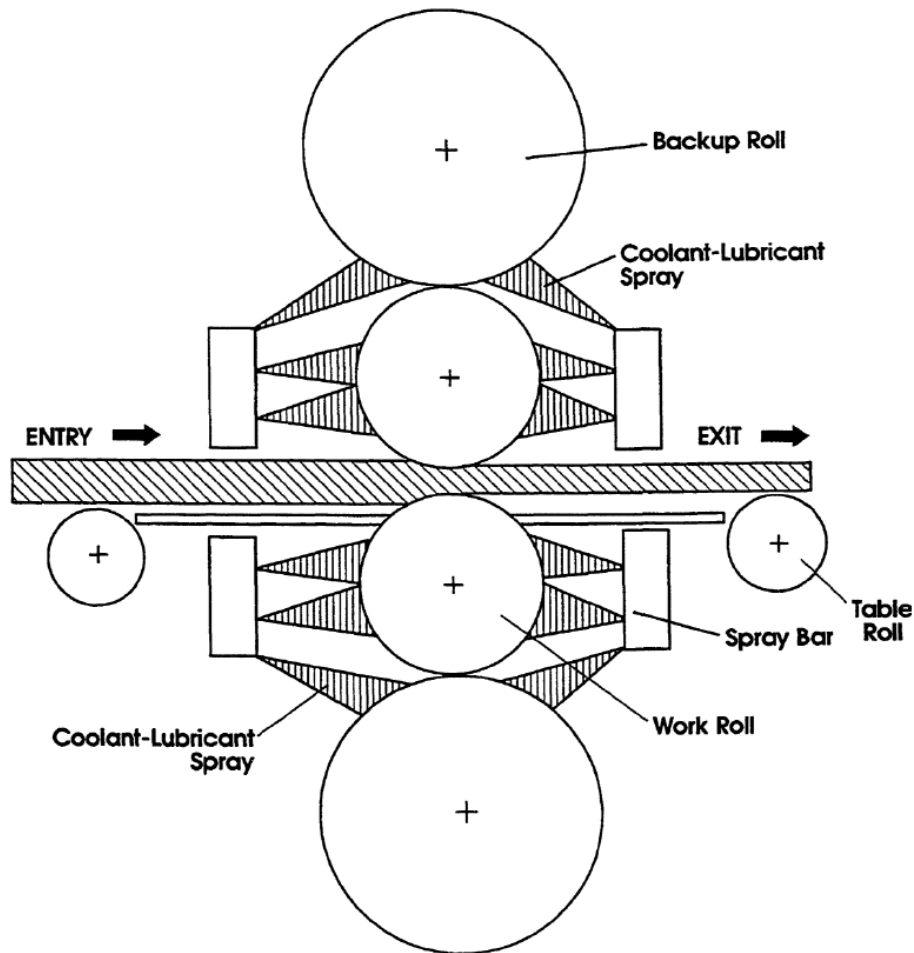


Figure 26: A rolling mill coolant/lubricant system (schematic). [2]

Rolling work can be done at high temperature (over recrystallization temperature) called hot rolling, this high temperature avoid strain-hardening when deforming the sheet. Cold rolling work occurs at room temperature which permits strain-hardening as the metal is deformed, taking more energy to deform in cold work than hot work; cold work provides smoother finish surface than hot working, working cold the thinnest products as last rolling step. Hot mills roll sheet at rates of 600 m/min, cold work can roll sheet at rates up to 2135 m/min or higher. Some coolant/lubricant system is needed in both cold and hot rolling. Figure 26 shows a schematic representation of the cooling system in mill rolling.

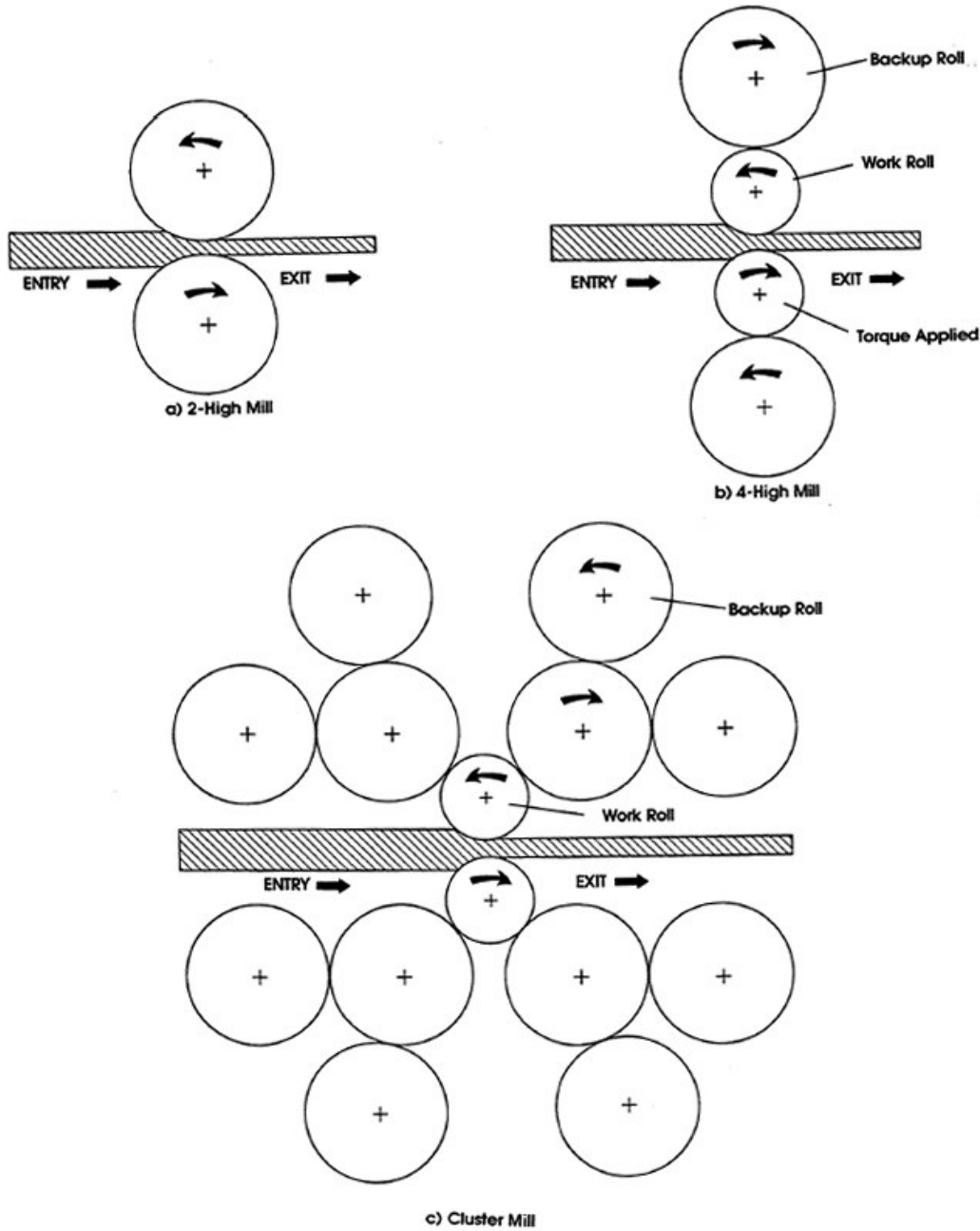


Figure 27: Common roll configurations: a)two-high, b)four high, c)cluster. [2]

Cold Rolling

Cold rolling is generally used to give a desired strength and temper and provide a final surface finish or reduce the sheet to a very small thickness. Aluminum alloys can be cold rolled to a thickness of 0.05mm, pure aluminum can reach 0.025mm thickness in cold rolling. The sheet is usually hot rolled and cold rolled as final step, as the hardening increases with cold work, it is needed more power to roll the sheet. As hardening increases, there will be a point where ultimate stress would be reached, cracking the sheet when cold work is excessive. When reflective surface on cold rolling is needed, it is produced with smaller thickness reduction, using highly polished work rolls. Small temperature changes may occur by the friction between the sheet and the rolls, increasing from room temperature to 80°C, coolant is needed for heat dispersion. At atomic level, when cold rolling is applied to the material, it tends to break and offset the crystallographic planes, increasing the number of dislocations making the material harder and stronger, know as hardening process.

Hot Rolling

Preheating is needed for hot rolling, sometimes hot rolling is done after casting taking advantage of the already high temperature of the casted sheets, however the quality of these rolled sheet is poor because it needs scalping for high surface quality after rolling. Sheets are introduced into furnace for heating after scalping, generally reaching over recrystallization temperature for hot rolling, there can be multiple stands or rolls decreasing the thickness gradually, Figure 28 shows this multiple stands each one reducing more the thickness of the coil.

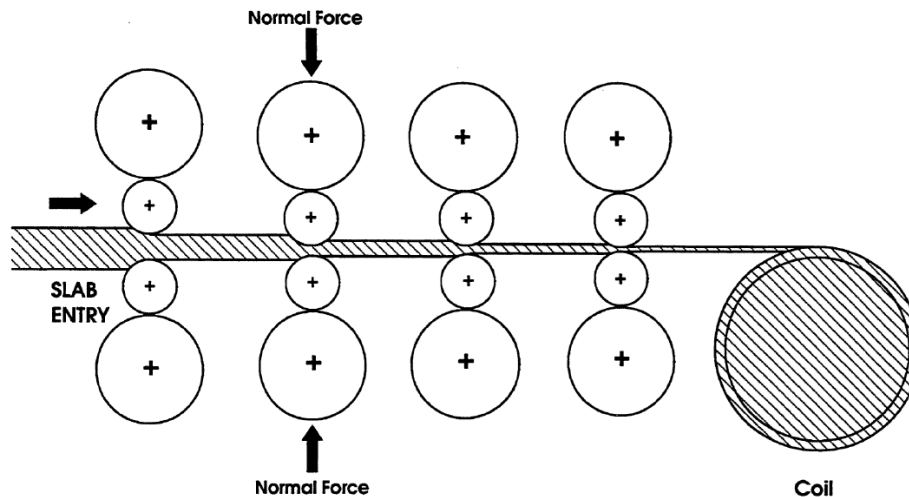


Figure 28: A four stand tandem rolling mill with take-up coil (schematic). [2]

The crystallographic effects into the material due hot working is that it welds pores left by casting, increasing the density and strength of the material. It breaks up and distributes hard constituents of iron and silicon which have formed at grain boundaries, converting brittle cast alloy into ductile wrought alloy, because fragmented and distributed constituents offer less resistance to the internal metal flow necessary to ductility. The rolling temperature depends on the mechanical properties requirements of the sheet; high temperature of the sheet decreases the energy needed for plastic deformation and shaping, however corrosion and oxidation may occur at high temperature for some alloys.

Annealing

When cold rolling is applied, annealing is used before, after or between cold rolling operations; annealing consist in heating and slowly cooling the sheet, softening the material and stabilizing some tempered properties. Full or partial annealing may be applied as final stage to prepare the sheet to posterior manufacturing processes. When hot or cold working the sheet, some undesirable hardening levels may be reached, these unwanted precipitation hardening and residual stresses are relieved by taking the metal over the recrystallization temperature and stand long enough for the creation of new grain boundaries relieving internal residual stresses.

Full annealing keeps the metal long enough for fully recrystallization process, converting the alloys into their softest, most ductile, most workable condition; it is designate as the O-temper. Fully annealing process takes approximately 2 hours at a temperature in the range of 335-370 °C to remove cold work or 400-425°C to counteract heat treatment. H1 and H3 tempers are produced by some hardening and fully annealing process, called rolled-to-temper products.

Partial annealing makes only a portion of the recrystallization, keeping the material over the recrystallization temperature just a fraction of the total time needed for fully recrystallization to have an intermediate materials between fully soft and fully work hardening, typically designed as H2X tempers, strain hardened and partially annealed.

Quenching

The movement of the dissolved elements is more free through an alloy at the molten state, than once lattice is bully rigid, cool and rigid. At slow cooling, the dissolved dispersed elements would be partially squeezed out of the forming crystal lattice and would cluster in large particles with small strengthening influence; to prevent this response, quenching is performed to the alloy, cooling fast enough to avoid migration of dissolved elements, having a freezing effect, keeping the dissolved elements where they are, dispersed in a supersaturated solid solution, holding more alloying elements in solution at room temperature than would otherwise occur with a slow cooling.

high heat rates are reached with water or UCON as quenchant, milder quenching process such as water spray, hot or boiling water, air blast or water-mist fog are used for some alloys where heat treated properties are less sensitive to the high heat rates, these processes minimize distortion residual stress in the metal. High residual stresses in the sheet by quenching are generated, quenching heat rates are optimized to balance high metal quality, good dispersion of elements and low residual stresses.

Stretching

The metal sheet is summited to stretching to flatten it, the end are clamped by pneumatic jaws, tensing the plate, stretching to a specific deformation, this also relieves residual stress gradients. Figure 29 shows a schema of the process.

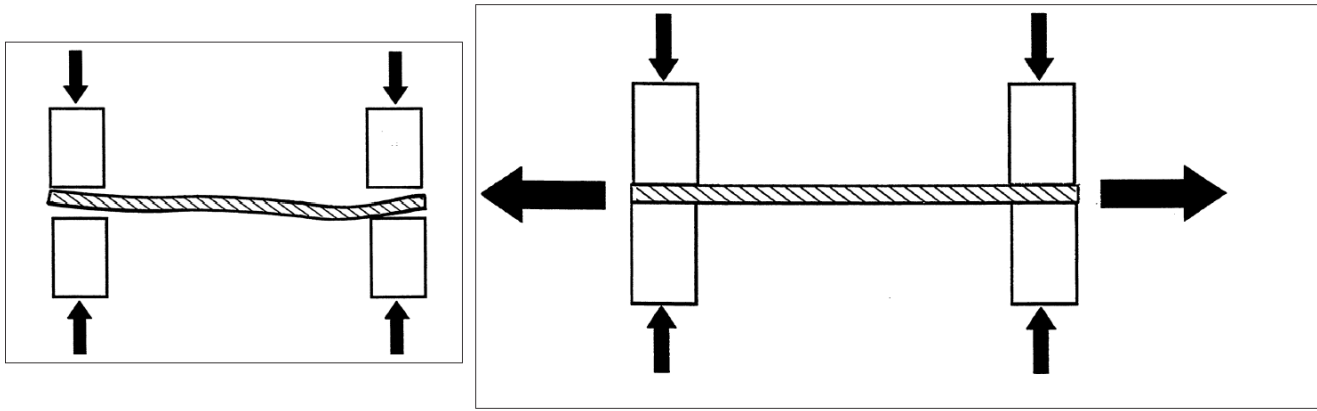


Figure 29: Schema of stretching process. [2]

Aging

Heat treatment process propose is to increase strength which is developed during its final step, precipitation hardening. The elements dissolved in a supersaturated solid solution can migrate through cool metal, even at room temperature but not with the same rate as it would do at high temperatures; atoms of dissolved alloying elements can slowly gather to form small precipitates with short distances between them, but not big particles. The number of small dislocation precipitates gives the alloy its mechanical properties of strength and hardness. Aging allows sufficient time for this to happen before the metal is finally used, solution heat treatment and quenching establish the conditions for dislocation pinning to occur.

Natural Aging

Natural aging occurs at room temperature, virtually maximum strength is reached in a short time, few days or weeks, or long term natural aging where effects are seen in years. 2024 alloy precipitation hardening is considerably complete after about four days at room temperature, achieving the T3 or T4 temper.

Artificial Aging

Some alloys harden more slowly at natural conditions, taking years for appreciable aging effects. The aging process is accelerated by increasing the temperature of the sheet, increasing the mobility of dissolved elements and allows them to precipitate more rapidly than at room temperature. Some combination may occur for strength (small amount of cold working followed by artificial aging). Temperature ratios are between 115-190°C during 5-48 hours. Artificial aging can be carried beyond the point of maximum alloy strength. Some specific mechanical properties can be achieved by promoting the controlled growth of somewhat larger precipitates, reducing strength and hardness. If temperature is reduced, aging process can be slowed down, it is used for some applications where post process will be applied.

Machining

Machining processes is often used for final shaping of an element, which as been previously casted, formed or shaped. These previous processes don't give the dimensional tolerances, surface roughness and complex geometries that can be performed in machining processes.

Machining encloses several processes which consist in material removal and surface finishing, thus machining is considered a secondary or final operation.

Figure 30 shows some of the complex shapes for components done by machining processes. These parts would not be possible to make with the accuracy and quality required with any forming process.

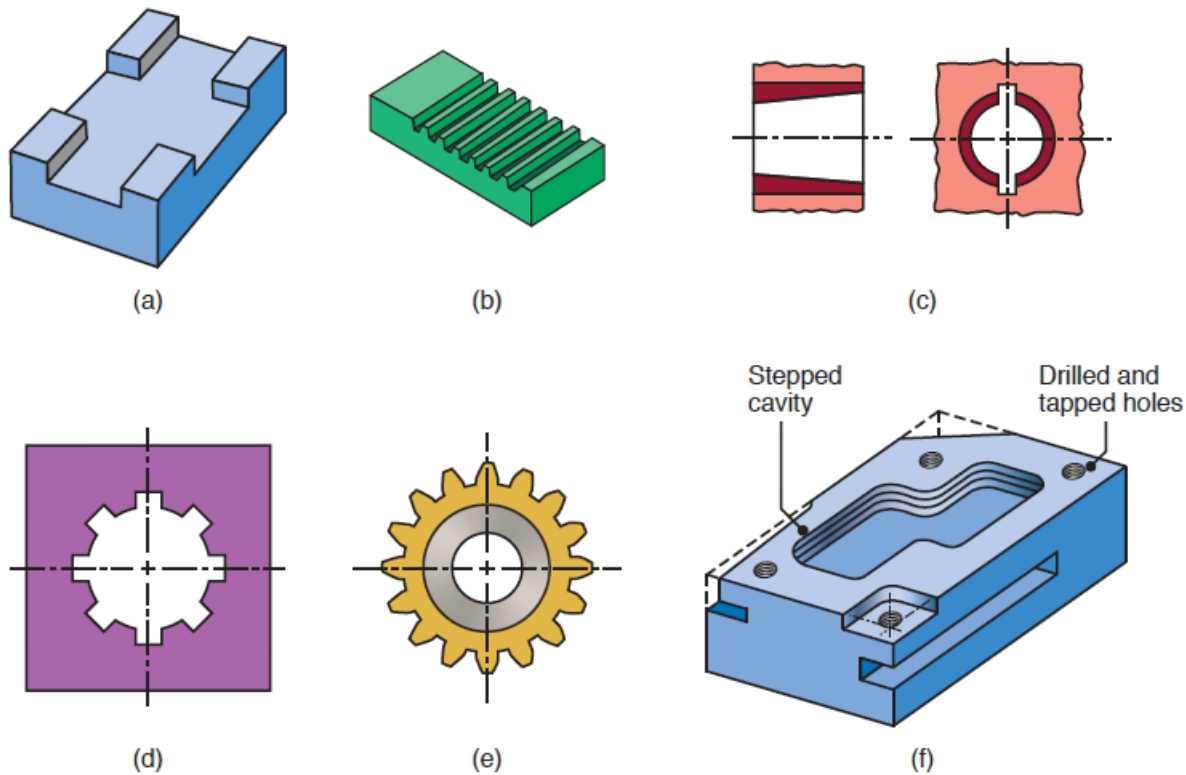


Figure 30: Typical shapes in machining processes. [18]

The general machining manufacturing processes are turning, boring, drilling, milling, planing, shaping, broaching and swing; Table 9 taken from [18] encloses these machining processes, providing some characteristics of each process and typical tolerances in each process. Machining process in general have very close tolerance values, these processes give the parts with highest quality and dimensional accuracy.

Figure 31 shows the turning process, which consist in removal of material (chip) from a turning part with a cutting tool or insert; the variables of process to be defined are the rotational speed of the part (generally in rpm) the depth of cut (mm or in) and the feed (mm/rev or in/rev); these variables define the machining time and quality of the component. The machining range for each variable are specific for each material depending the properties and compatibility to the process.

Process	Characteristics	Commercial tolerances (\pm mm)
Turning	Turning and facing operations are performed on all types of materials; requires skilled labor; low production rate, but medium to high rates can be achieved with turret lathes and automatic machines, requiring less skilled labor	Fine: 0.05-0.13 Rough 0.13 Skiving: 0.025-0.05
Boring	Internal surfaces or profiles, with characteristics similar to those produced by turning; stiffness of boring bar is important to avoid chatter.	0.025
Drilling	Round holes of various sizes and depths; requires boring and reaming for improved accuracy; high production rate, labor skill required depends on hole location and accuracy specified.	0.075
Milling	Variety of shapes involving contours, flat surfaces, and slots; wide variety of tooling; versatile; low to medium production rate; requires skilled labor.	0.13-0.25
Planing	Flat surfaces and straight contour profiles on large surfaces; suitable for low-quality production; labor skill required depends on part shape.	0.08-0.13
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; suitable for low-quality production; labor skill required depends on part shape.	0.05-0.13
Broaching	External and internal flat surfaces, slots, and contours with good surface finish; costly tooling; high production rate; labor skill required depends on part shape.	0.025-0.15
Sawing	Straight and contour cuts on flats or structural shapes; not suitable for hard materials unless the saw has carbide teeth or is coated with diamond; low production rate; requires only low skilled labor.	0.8

Table 9: Machining processes description and characteristics. [18]

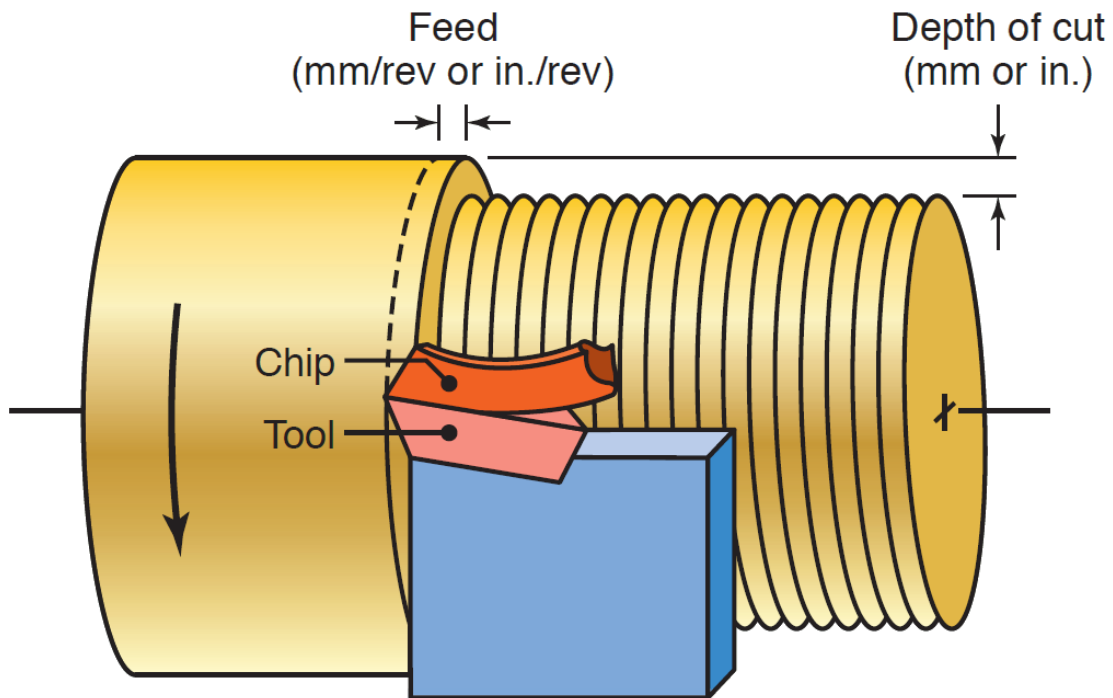


Figure 31: Variables in machining processes. [18]

Figure 33 shows some machining processes described in table 9, all performed in a lathe machine. Figure 32 shows the basic elements of the conventional lathe machine. The spindle holds the workpiece and rotate it (max 4000rpm), it is powered by a motor; the rotation speed and feed are defined and controlled by the internal gears and carriage, the deep is manually controlled. The CNC lathe are controlled electronically in totality, increasing precision and ease to use and control.

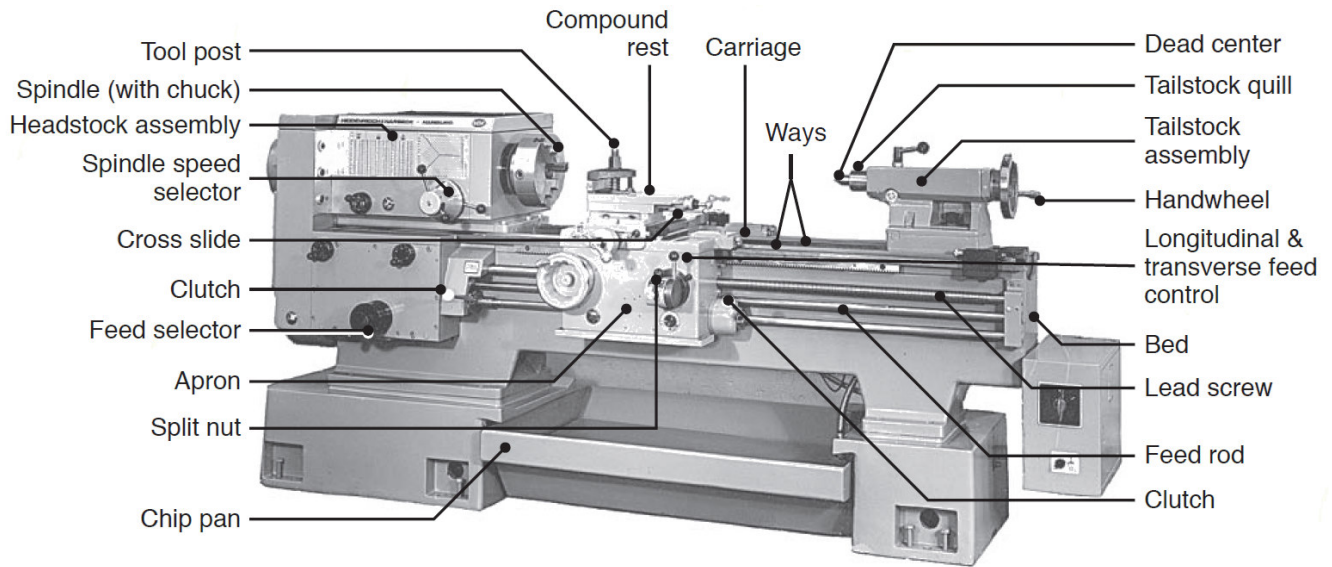


Figure 32: Components of a conventional lathe machine. [18]

Milling machining process removes the materials through the movement (rotation rpm) of the mill tool, in this case the workpiece is fixed. Same parameters are used, rotation speed of the mill (rpm), linear movement of the fixed workpiece or feed (mm/s in/s) and depth of cut (mm or in). Figure 34 shows examples of milling operations, slab and end milling. Milling operations are performed in a machining center, Figure 35 shows a horizontal-spindle machining center, equipped with an automatic tool changer. Tool magazines in such machines can store as many as 200 cutting tools, each with its own holder.

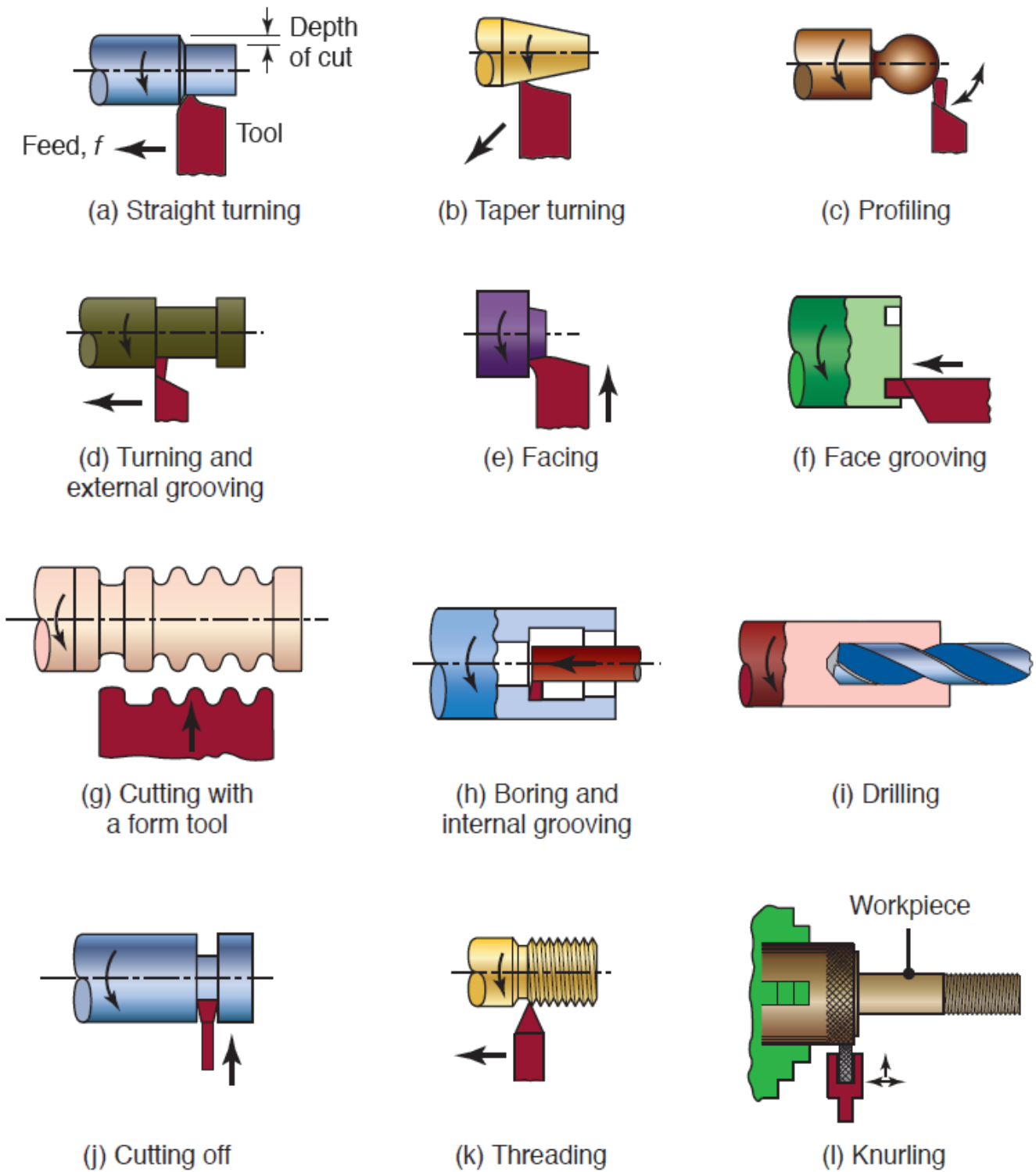


Figure 33: Machining manufacturing processes. [18]

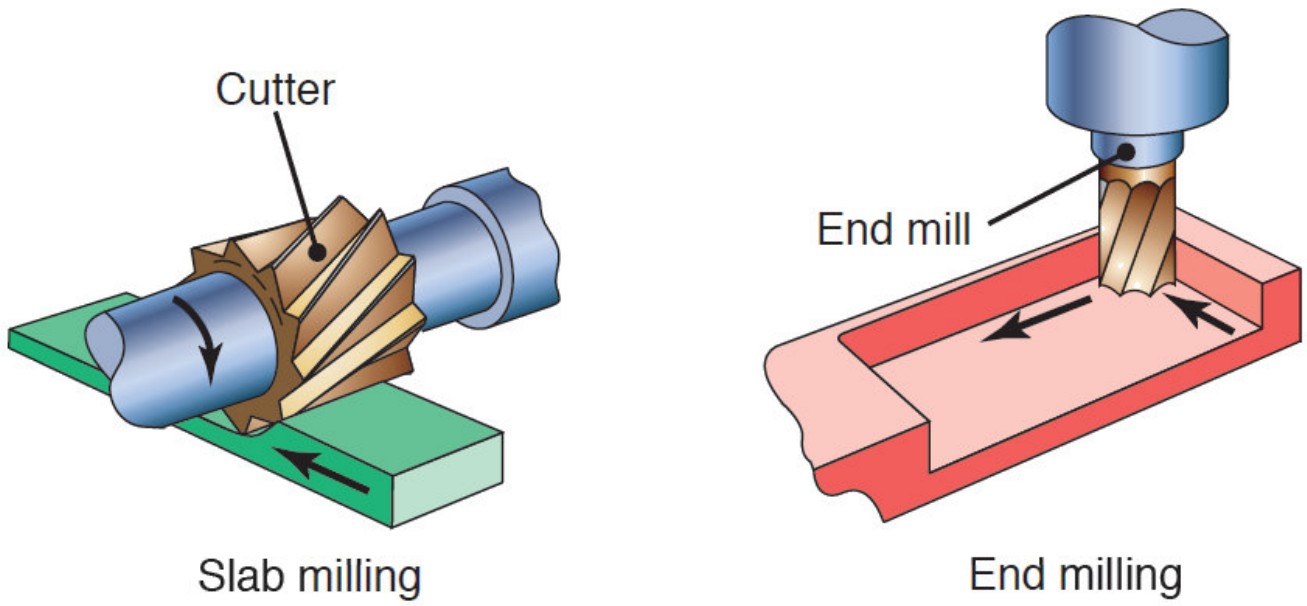


Figure 34: Examples of milling machining operations. [18]

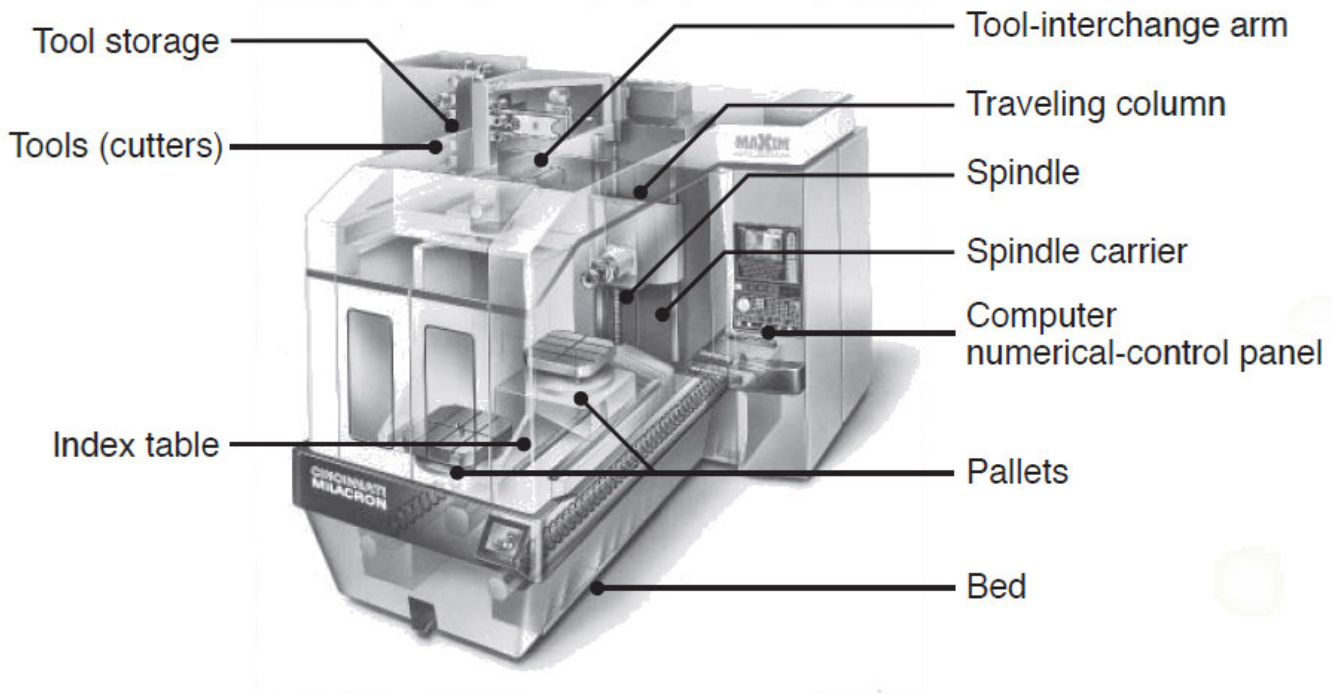


Figure 35: Horizontal-spindle machining center. [18]

II FEM Software

This chapter provides the bases of finite element method for numerical analysis, method used for machining distortion simulation and optimal position finding. Open source software is used for workflow integration and ease manipulation and control for the user; a general description and exploration of each software used in this project is presented in this chapter, this information is consulted in official web pages of the software.

Finite Element Method

The human mind is not capable to handle the complexity of its surrounding and the physical phenomenas involved in one operation; for treatment, the human mind starts subdividing every system into individual smaller and ease to handle components, whose behavior is readily understood, then the whole system is rebuilt from its individual elements, having a complete panorama of the initial complex phenomena.

For complex analysis an approximative model is obtained using a finite element of well defined components, discretizing the initial problem. In some conditions the subdivision is continued indefinitely and the problem can be only defined using the mathematical fiction of an infinitesimal. This is handled with differential equations implying a finite number of elements, this analysis are continuous systems.

These discretized problems can be readily solved with computational sources even whit a large number of elements. Conversely, continuous problems can only be solved exactly by mathematical manipulations due the finite capacity of a computer, however approaches to finite portions of a continuum domain with discrete elements have been developed, making possible approximative solutions for continuous problems by a finite discretization of a portion of the system.

Reference [21] enunciate 7 steps for the finite element method:

Step 1- Idealization

The physical phenomena is idealized, simplifying the problem as much as possible, reducing the dimensions of the system, Figure 36 shows idealization in dimensions of a component. The support conditions can be idealized reducing applied forces to a single point (node).

Some geometrical details can be avoid, representation of complex structures or joints can be simple represented by generic geometries avoiding small holes and fillets which are not significant to the analysis but considerably increase the complexity of the mesh process.

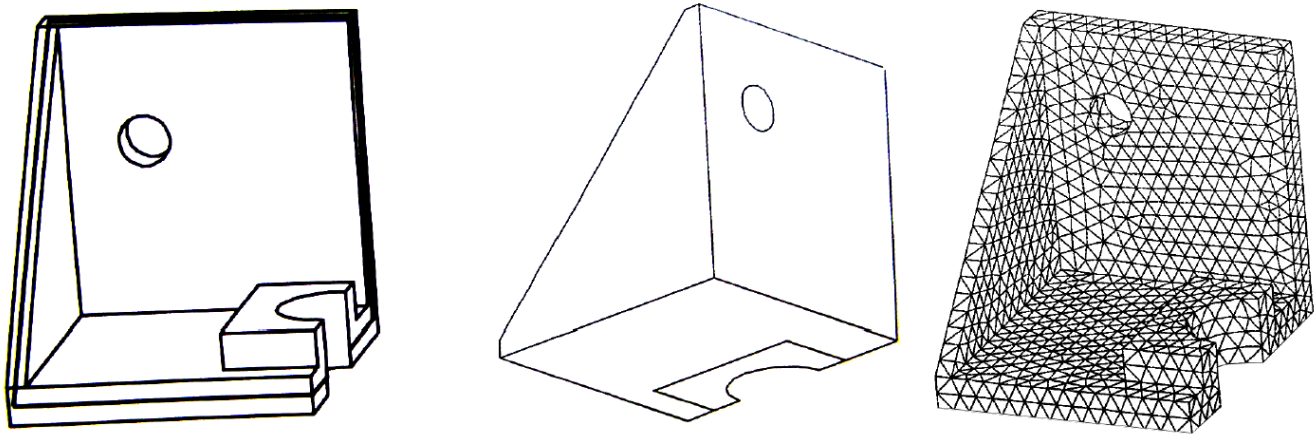


Figure 36: This 3d part can be idealized by 2D elements (plates) or 3D solid elements. [21]

Figure 37 shows a simplified model of a roof truss, the method is used not to represent the real system with the highest accuracy and fidelity, but to simplify it into basic elements, reducing the system to a finite number of elements and equations ease to solve by the computer. It is not about representing the most descriptive geometry but the most simple one which take all the important characteristics of the real structure (dimensions, interactions, etc.).

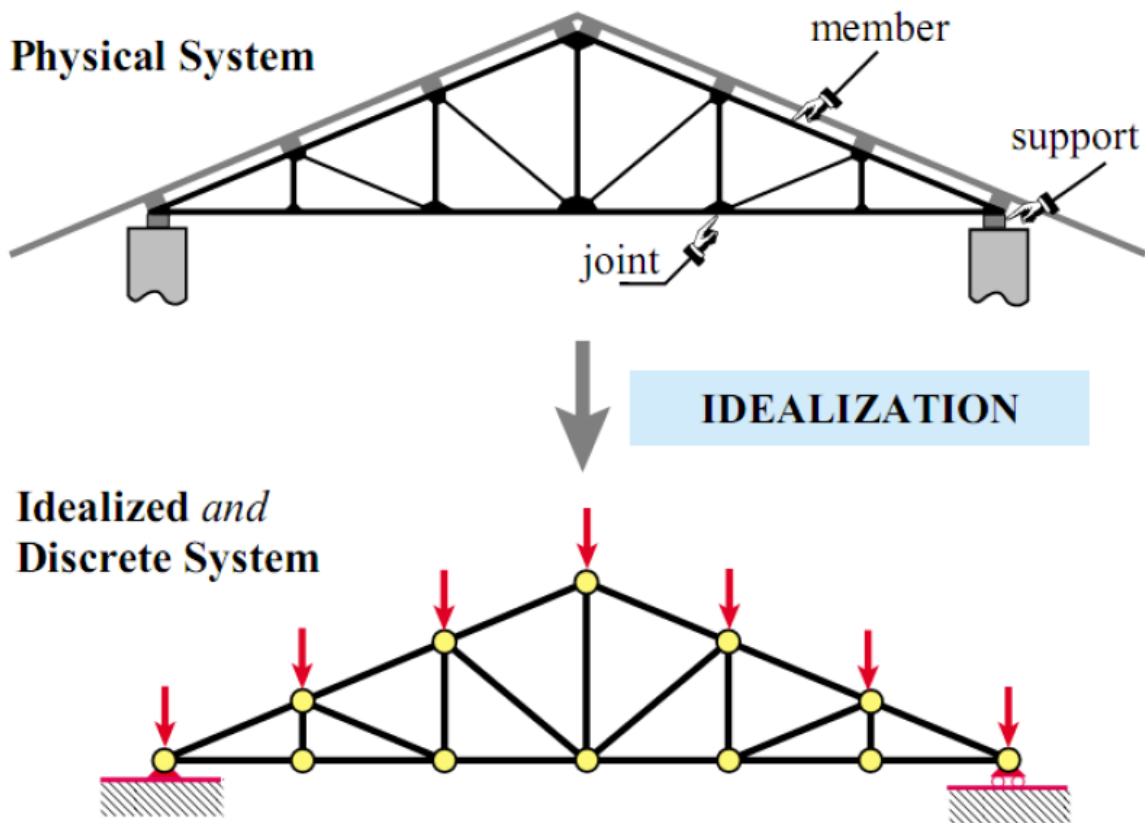


Figure 37: Idealization of a roof truss. [21]

Step 2- Discretization

For the computational analysis, the system is divided into simple finite number of elements, Figure 36 shows the initial geometry represented with many tetrahedral solid elements. This discretization reduces the big complex problem into small elements that can be treated individually to integrate them into a general solution.

Step 3- Choice of the type of element

The choice of the type of element is very important for the results of the analysis, every type of element has its own theory involved, Figure 38 shows the basic elements in fem softwares.

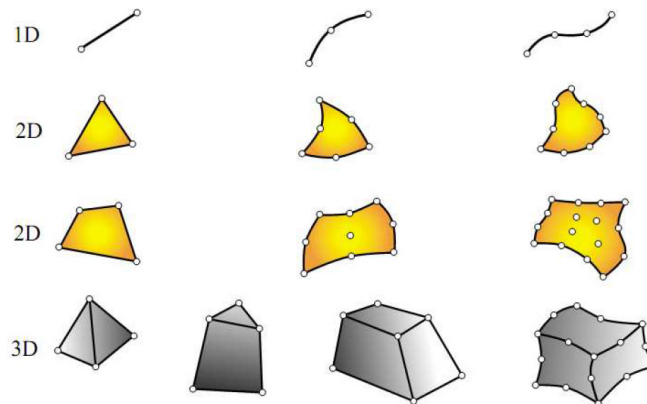


Figure 38: Typical finite element geometries. [21]

Step 4- Assembly of the discrete elements

The equations for each element in the FEM mesh are assembled into a set of global equations that model the properties and characteristics of the entire system.

Step 5- Application of Boundary Conditions

Some known values for certain primary unknowns are considered boundary conditions, without the statement of these conditions, the system cannot converge into a solution. The correct definition of boundary conditions gives an appropriate and approach solution of the system.

Step 6- Solve for Primary Unknowns

The modified global equations are solved for the primary unknowns at the nodes.

Step 7- Calculate Derived Variables

Calculated using the nodal values of the primary variables.

FreeCAD

The description of this open source software found in its official web site [15] is showed below:

FreeCAD is a general purpose parametric 3D CAD modeler. The development is completely Open Source (LGPL license). FreeCAD is aimed directly at mechanical engineering and product design but also fits in a wider range of uses around engineering, such as architecture or other engineering specialties.

FreeCAD features tools similar to Catia, SolidWorks or Solid Edge, and therefore also falls into category of MCAD, PLM, CAx and CAE. It is a feature based parametric modeler with a modular software architecture which makes it easy to provide additional functionality without modifying the core system. As with many modern 3D CAD modelers it has many 2D components in order to sketch 2D shapes or extract design details from the 3D model to create 2D production drawings, but direct 2D drawing (like AutoCAD LT) is not the focus, neither are animation or organic shapes (like Maya, 3ds Max, Blender or Cinema 4D), although, thanks to its wide adaptability, FreeCAD might become useful in a much broader area than its current focus.

FreeCAD makes heavy use of all the great open-source libraries that exist out there in the field of Scientific Computing. Among them are OpenCascade, a powerful CAD kernel, Coin3D, an incarnation of Open Inventor, Qt, the world-famous UI framework, and Python, one of the best scripting languages available. FreeCAD itself can also be used as a library by other programs. FreeCAD is also fully multi-platform, and currently runs flawlessly on Windows and Linux/Unix and Mac OSX systems, with the exact same look and functionality on all platforms. FreeCAD project was started as far as 2001, it is maintained and developed by a community of enthusiastic developers and users. They work on FreeCAD voluntary, in their free time. They cannot guarantee that FreeCAD contains or will contain everything you might wish, but they will usually do their best!.

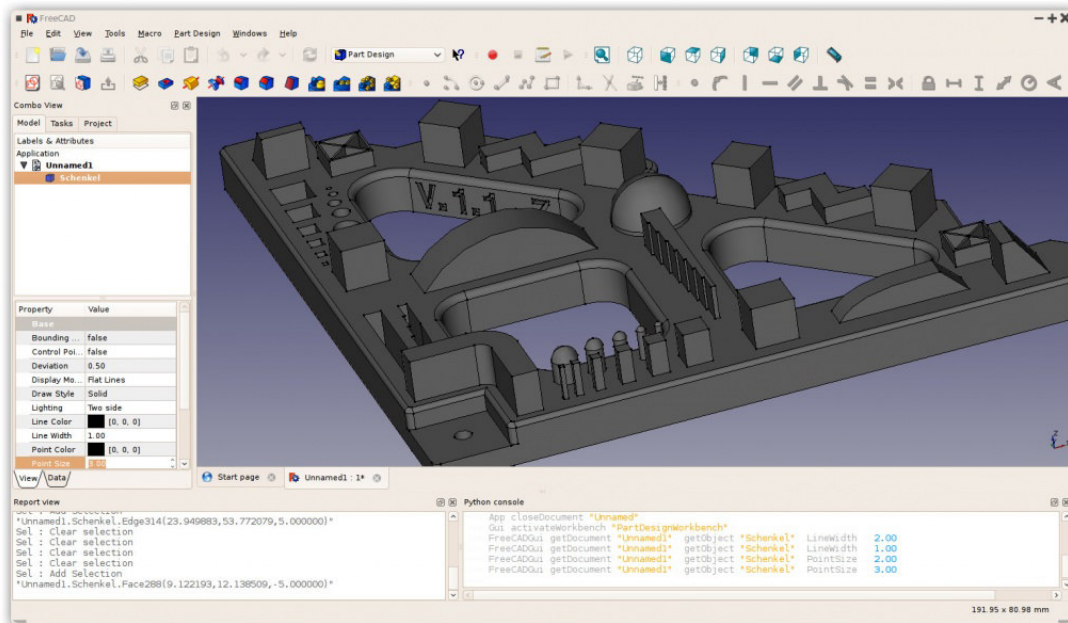


Figure 39: FreeCAD interface. [15]

*FreeCAD contains a complete Open CASCADE Technology-based **geometry kernel** allowing complex 3D operations on complex shape types, with native support for concepts like brep, nurbs curves and surfaces, a wide range of geometric entities, boolean operations and fillets, and built-in support of STEP and IGES formats.*

*It contains a full **parametric model**. All FreeCAD objects are natively parametric, which means their shape can be based on properties or even depend on other objects, all changes being recalculated on demand, and recorded by the undo/redo stack. New objects types can be added easily, that can even be fully programed in Python.*

*FreeCAD has a **modular architecture** that allow plugins (modules) to add functionality to the core application. Those extensions can be as complex as whole new applications programmed in C++ or as simple as Python scripts or self-recorded macros. You have complete access from the Python built-in interpreter, macros or external scripts to almost any part of FreeCAD, being geometry creation and transformation, the 2D or 3D representation of that geometry (scenegraph) or even the FreeCAD interface.*

*FreeCAD can import/export to **standard formats** such as STEP, IGES, OBJ, STL, DXF, SVG, STL, DAE, IFC or OFF, NASTRAN, VRML in addition to FreeCAD'S native Fcstd file format. The level of compatibility between FreeCAD and a given file format can vary, since it depends on the module that implements it.*

*FreeCAD has a **Sketcher** with constraint-solver, allowing to sketch geometry-constrained 2D shapes. The sketcher currently allows you to build several types of constrained geometry, and use them as a base to build other objects throughout FreeCAD.*

*A **Robot simulation** module is included which allows to study robot movements. The robot module already has an extended graphical interface allowing GUI-only workflow.*

*It contains a **Drawing sheets** module that permit to put 2D views of your 3D models on a sheet. This modules then procedures ready-to-export SVG or PDF sheets. The module is still spare but already features powerful Python functionality.*

*FreeCAD has a **Rendering** module that can export 3D objects for rendering with external renderers. Currently only supports povray and LuxRender, but is expected to be extended to other renderers in the future.*

*It counts with an **Architecture** module that allows BIM-like workflow, with IFC compatibility.*

*A **Path module** is dedicated to mechanical machining like milling (CAM), and is able to output, display and adjust G code.*

Multi-platform	It runs and behaves exactly the same way on Windows Linux and macOS platforms.
Full GUI application	FreeCAD has a complete Graphical User Interface based on the famous Qt framework, with a 3D viewer based on Open Inventor, allowing fast rendering of 3D scenes and a very accessible scene graph representation.
Command line application	FreeCAD also runs as a command line application, with low memory footprint. In command line mode, FreeCAD runs without its interface, but with all its geometry tools. It can be, for example, used as server to produce content for other applications.
Python module	FreeCAD can be imported as a Python module, inside other applications that can run with Python scripts, or in a Python console. Like in console mode, the interface part of FreeCAD is unavailable, but all geometry tools are accessible.
Workbench concept	In the FreeCAD interface, tools are grouped by workbenches. This allows to display only the tools used to accomplish a certain task, keeping the workspace uncluttered and responsive, and the application fast to load.
Plugin/Module framework	Plugin/Module framework for late loading of features/data-types. FreeCAD is divided into a core application and modules, that are loaded only when needed. Almost all the tools and geometry types are stored in modules. Modules behave like plugins, and can be added or removed to an existing installation of FreeCAD.
Parametric associative document objects	All objects in a FreeCAD document can be defined by parameters. Those parameters can be modified on the fly, and recomputed anytime. The relationship between objects is also stored, so modifying one object also modifies its dependent objects.
Parametric primitive creation	Parametric primitive creation like box, sphere, cylinder, etc.
Graphical modification operators	Graphical modification operators like translation, rotation, scaling, mirroring, offset (trivial or after Jung/Shin/Choi) or shape conversion, in any plane of the 3D space.
Boolean operations	Boolean operations like union, difference and intersect.
Graphical creation of simple planar geometry	Graphical creation of simple planar geometry like lines, wires, rectangles, arcs or circles in any plane of the 3D space.
Modeling	Modeling with straight or revolution extrusions, sections and fillets.
Topological components	Topological components like vertices, edges, wires and planes (via Python scripting).
Testing and repairing tools for meshes	Solid test, non-two-manifolds test, self-intersection test, hole filling and uniform orientation.
Annotations	Annotations like texts or dimensions.
Undo/Redo framework	Everything is undo/redoable, with access to the undo stack, so multiple steps can be undone at a time.
Transaction management	The undo/redo stack stores document transactions and not single actions, allowing each tool to define exactly what must be undone or redone.
Built-in scripting framework	FreeCAD features a built-in Python interpreter, and an API that covers almost any part of the application, the interface, the geometry and the representation of this geometry in the 3D viewer. The interpreter can run single commands up to complex scripts, in fact entire modules can even be programmed completely in Python.

Table 10: FreeCAD general features. [15]

Built-in Python console	Built-in Python console with syntax highlighting, autocomplete and class browser: Python commands can be issued directly in FreeCAD and immediately return results, permitting scriptwriters to test functionality on the fly, explore the contents of the modules and easily learn about FreeCAD internals.
User interaction mirroring on the console	Everything the user does in the FreeCAD interface executes Python code, which can be printed on the console and recorded in macros.
Full macro recording & editing	The Python commands issued when the user manipulates the interface can then be recorded, edited if needed, and saved to be reproduced later.
Compound (ZIP based) document save format	FreeCAD documents saved with .fcstd extension can contain many different types of information, such as geometry, scripts or thumbnail icons. The .fcstd file is itself a zip container, so a saved FreeCAD file has already been compressed.
Fully customizable/scriptable Graphical User Interface	The Qt-based interface of FreeCAD is entirely accessible via the Python interpreter. Aside from the simple functions that FreeCAD itself provides to workbenches, the whole Qt framework is accessible too, allowing any operation on the GUI, such as creating, adding, docking, modifying or removing widgets and toolbars.
Thumbnailer	(Linux systems only at the moment). The FreeCAD document icons show the contents of the file in most file manager applications such as Gnome's Nautilus.
A modular MSI installer	This allows flexible installations on Windows systems. Packages from Ubuntu systems are also maintained.

Table 11: FreeCAD general features (Continuation). [15]

The diverse characteristics of this open source software gives the required flexibility needed to encapsulate the code into a friendly user interface, adapted to shop-floor use. The integration with CalculiX and R software (open source softwares) is achieved by the development of the FreeCAD module (Part Distortion module), having the computational tools required by the workflow in an easy to handle software interface (GUI).

CalculiX

The description of this open source software found in its official web site [16] is showed below:

CalculiX is a package designed to solve field problems. The method used is the finite element method. With CalculiX Finite Element Models can be build, calculated and post-processed. The pre- and post-processor is an interactive 3D-tool using the OpenGL API. The solver is able to do linear an non-linear calculations. Static, dynamic and thermal solutions are available. Both programs can be used independently. Because the solver makes use of the abaqus input format it is possible to use commercial pre-processors as well. In turn the pre-processor is able to write mesh related data for nastran, abaqus, ansys, code-aster and for the free-cfd codes dolfyn, duns, ISAAC and OpenFOAM. A simple step reader is included. In addition external CAD interfaces like vda_to_fbd are available. The program is designed to run on Unix platforms like Lunix and Irix computers but also on MS-Windows. The CalculiX package was developed by a team of enthusiasts in their raw spare time. They are employees of MTU Aero Engines in Munich, Germany which granted the publication.

For a quick overview of the capabilities of CalculiX the results of an investigation of a small jet engine are presented. The jet engine was build around a turbo-charger rotor in the early 90's by Andreas Funke and Klaus Wittig. The FE-model was build from scratch with CalculiX and the compressor- and turbine models together with solver input files can be found in the distribution. The calculations were done to determine the burst-speed and the highest allowable rotational speed concerning low cycle fatigue and creep. In addition the eigenfrequencies were calculated to determine possible resonances with the vanes. The models are meshed with 20 noded brick elements with reduced integration. The right and left side of the disks are connected by cyclic symmetry equations which allow to calculate eigenvalues and mode-shapes for certain nodal diameters of a rotational symmetric volume based only on a segment of the structure. The compressor is made of casted aluminum alloy (AlSi-C355) and the turbine of a high temperature alloy (Inco 713C) and both are loaded by pure centrifugal force.

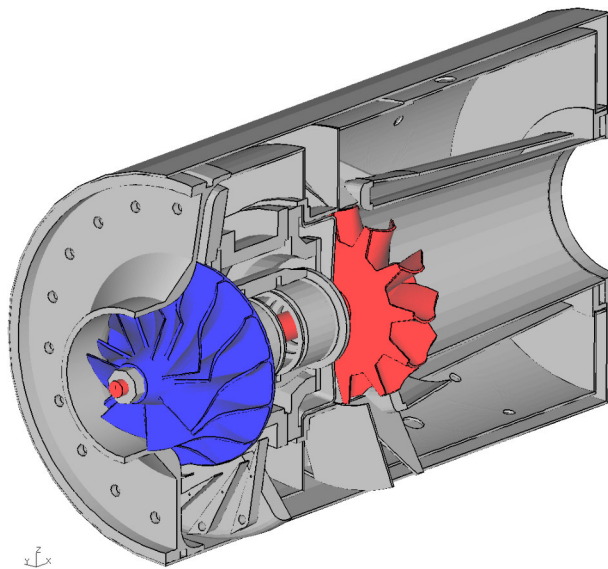


Figure 40: CalculiX FE-Model of a jet engine turbo-charger compressor (blue) and turbine(red).CalculiX

R

There are two R concepts, the programming language and the open source software used to run the R code, reference [17] describes both concepts and gives an overall introduction:

R (the programming language) was created in the early 1990's by Ross Ihaka and Robert Gentleman, then both working at the University of Auckland. It is based upon the S language that was developed at Bell Laboratories in the 197's, primarily by John Chambers.

R (the software) is a GNU project, reflecting its status as important free and open source software. Both the language and the software are now developed by a group of (currently) 20 people known as the R Core Team.

The fact that R's history dates back to the 1970's is important, because it has evolved over the decades, rather than having been designed from scratch (contrast this with, for example, Microsoft's .NET Framework, which has a much more "created" feel). As with life-forms, the process of evolution has led to some quirks and inconsistencies. The upside of the more free-form nature of R (and the free license in particular) is that if you don't like how something in R is done, you can write a package to make it do things the way that you want. Many people have already done that, and the common question now is not "Can I do this in R?" but "Which of the three implementations should I use?"

R is an interpreted language (sometimes called a scripting language), which means that your code doesn't need to be compiled before you run it. It is a high-level language in that you don't have access to the inner working of the computer you are running your code on; everything is pitched toward helping you analyze data.

R supports a mixture of programming paradigms. At its core, it is an imperative language (you write a script that does one calculation after another), but it also supports object-oriented programming (data and functions are combined inside classes) and functional programming (functions are first-class objects; you treat them like any other variable, and you can call them recursively). This mix of programming styles means that R code can bear a lot of similarity to several other languages. The curly braces mean that you can write imperative code that looks like C (but the vectorized nature of R means that you have fewer loops). If you use reference classes, then you can write object-oriented code that looks a bit like C# or Java. The functional programming constructs are Lisp-inspired (the variable-scoping rules are taken from the Lisp dialect, Scheme), but there are fewer brackets. All this is a roundabout way of saying that R follows the Perl ethos:

There is more than one way to do it. -Larry Wall

The importance of this open source software is that it can be used for statistical analysis, useful for sensitive studies of parameters and variables involved in the distortion after machining of the structural components. Design of experiments is used for several analysis options integrated into the FreeCAD Part Distortion module. General graphs of results can be generated as well in this software, helping the user to interpret results and chose a proposed optimal solution that best match the industrial requirements.

III Workflow Description

In this chapter the proposed solution for machining distortion reduction is described through the shop floor level workflow, exploring each step and giving clear bases of the process. Basic considerations are exposed based on previous work and industrial experience. This method is valid only for rolled plate as the residual stress is assumed to be in plane-stress state (stresses in thickness direction are negligible) and homogeneous (residual stress state on one end of the plate is the same as that at the other end).

Fist published by Pechiney industry in the 1990's, the method has proven effectiveness in predicting distortion. It is assumed that the part is perfectly clamped throughout the machining process, allowing to simplify the simulation into a single step operation (all material is removed in one go), otherwise it would be required to simulate successive machining operations and progressive removal of material due significant distortion of the part during machining process if it is not fixed during all operations, or it is relaxed. This would require more computationally intensive and much more human effort in pre-processing, since all machining operations would have to be defined in detail.

The distortion after machining is sensitive to initial residual stress profiles in the rolled plates, sensitive, design exploration and uncertainty propagation studies are carried out to predict optimal rolled plate thickness and part offset to minimize part distortion and buy-to-fly ratios defined as the ratio of bounding box volume.

$$buy - to - fly \ ratio = (length_{min \ vol \ bounding \ box})(breadth_{min \ vol \ bounding \ box})(plate \ thickness)$$

The workflow described in Reference [11] is presented in this chapter, exploring the bases of the steps for machining distortion reduction going from residual stress characterization to mathematical function fit and numerical simulation to find optimal solution.

Residual Stress Measurement

Residual stresses influence the mechanical properties of materials, fatigue life, dimensional stability, corrosion resistance, brittle fracture and distortion (the focused problem due residual stresses analyzed in this thesis work) [14]. These effects are an important economic aspect due repairs and restoration in structural parts after production. Residual stress analysis is compulsory when designing an structural component to estimate actual resistance and durability during productive life.

Reference [13] synthesizes the residual stress measurement methods and their classification. The methods are classified in non destructive, semi destructive and destructive, Figure 41 shows this classification.

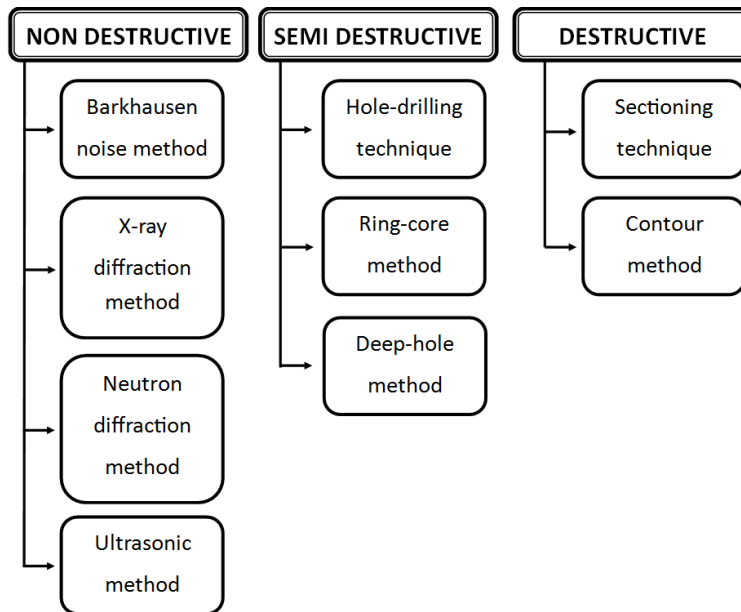


Figure 41: Residual stresses measuring techniques. [13].

Non destructive methods can measure residual stresses without modifying or encroaching the part, however, these methods are limited to determine residual stresses up to a maximum measurement depth of 0.05mm. Neutron diffraction method can measure to depths of many centimeters but it is constrained to measure a volume no smaller than a cube 1 to 2mm on side. It is not possible to fully determine residual stress profile in rolled plates by non-destructive methods limited to 1mm depth, moreover these techniques require complex equipment and skilled workers. Reference 42 shows the capabilities in measuring residual stresses for non destructive, semi destructive and destructive methods.

Semi destructive and destructive methods require material removal from the structure, extracting measurements through all the thickness. The stress is inferred from displacement after partially or totally releasing of residual stress upon material removal, linear elasticity analysis is used to estimate residual stresses. Destructive and semi destructive methods needs dedicated equipment such strain gauge, making inappropriate for practical industrial exploitation.

Residual stresses in rolled plates are inevitable due the manufacturing processes involved during the plates production (full processes extensively described in chapter I), quenching process is one of the most important processes, after rolling, the plate is induced to high temperatures to reach desirable mechanical properties needed in aerospace structural components; the plate is then cooled rapidly generating very high temperature gradients through the plate with high heat fluxes, this process produces internal residual stresses into the plate being the principal variable causative of the distortion after machining of structural components. These residual stresses are relief by stretching the plates 1.5 to 3%. Figure 43 shows the residual stresses through thickness of a rolled plate after quenching and then stretched for rolling direction (L direction) and transverse direction (LT direction).

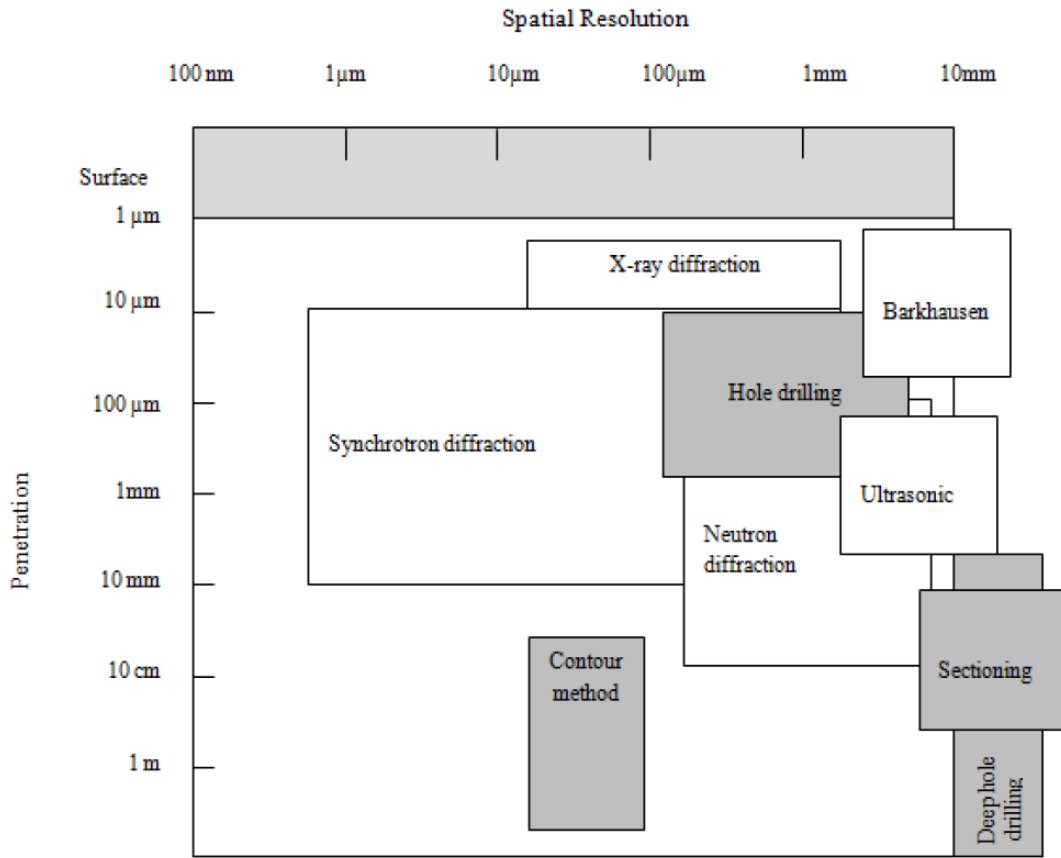


Figure 42: Schematic indicative of the approximate current capabilities of the various techniques. The destructive and semi destructive techniques are shaded gray. [13]

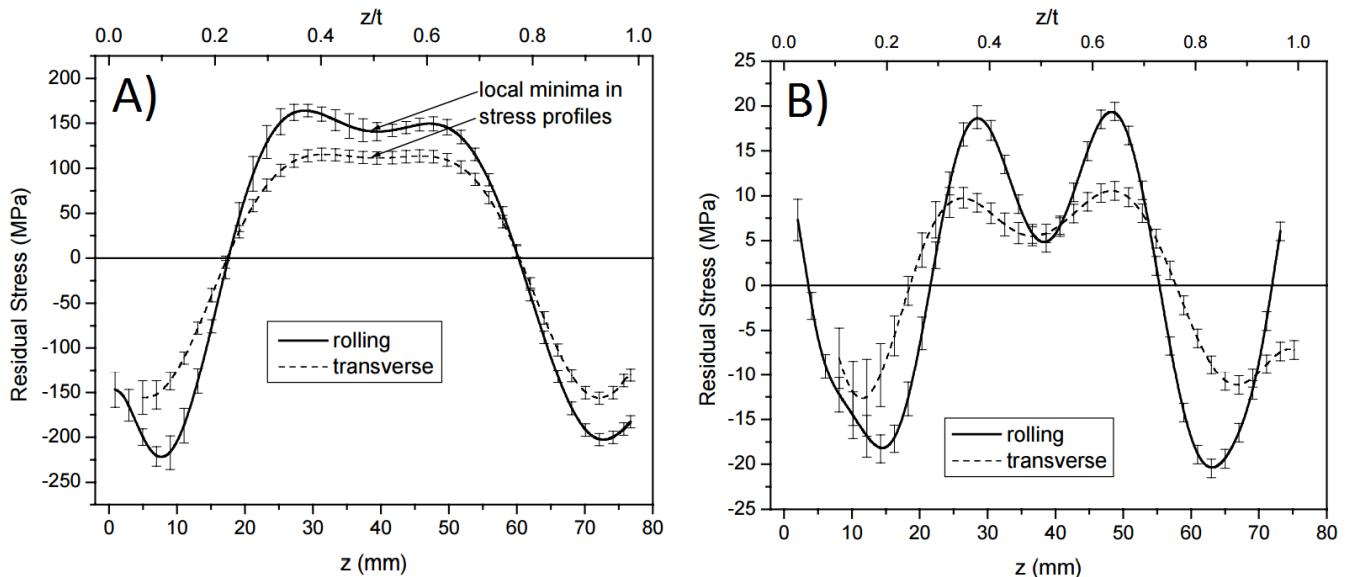


Figure 43: Typical residual stress through thickness profiles. A) Residual stresses in 7050-T74 aluminum plate. B) Residual stresses after stress relief in stretching (7050-T7451 aluminum plate). [12]

Modified Layer Removal Method

For full thickness residual stress measurement, a destructive method is developed, which can be performed in a conventional CNC machining center using displacements measurements from high resolution linear transducer. Figure 44 shows the CNC set up.



Figure 44: Residual stresses measurement system for a conventional CNC machine. [11]

For this method two specimens are needed, one cut from longitudinal direction (L), and the other one from the lateral direction (LT). Figure 45 shows the specimens taken from the rolled plate for residual stress measurement.

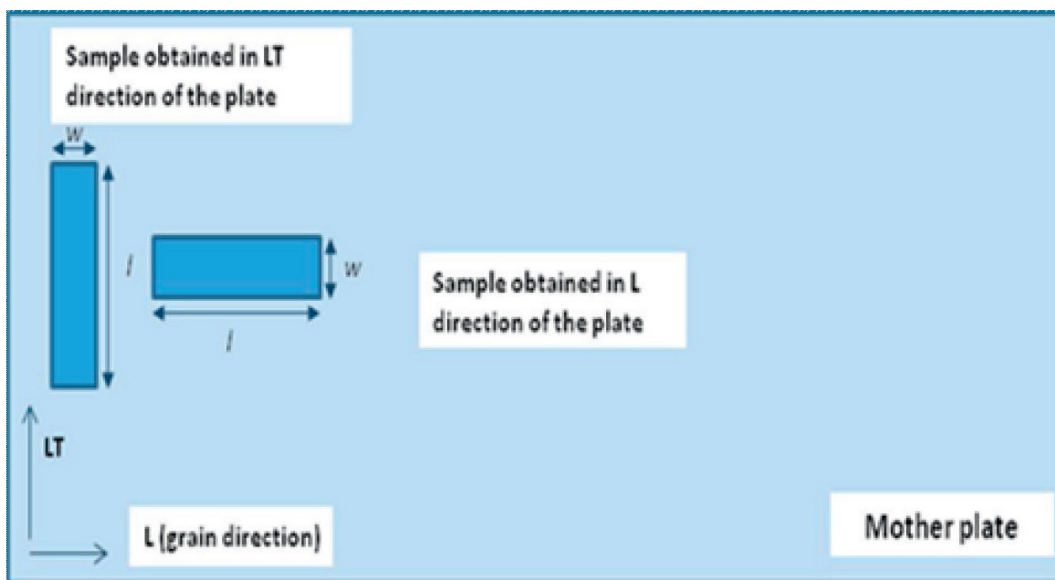


Figure 45: Test specimens for Modified Layer Removal Method. [11]

The layer removal method consists in measuring displacement after gradually removal of thin layer of material. The basic assumption is that the internal stresses varies with thickness producing mechanical potential energy. When energy is released from a layer of metal removed, it is carried to the remaining materials and results in residual stress redistribution, producing the part bending. The stress profile is assumed to be symmetrical with mid-plane because of the manufacturing process, the incremental milling can be stopped at half of the initial thickness, then residual stress magnitude is determined after processing the displacement measurements of each removal.

A CNC is chosen for residual stress measurement because of the familiarity of engineers at the shop-floor level, a jig has been designed and manufactured to ease the material characterization, it is easy to handle and assembly, helping the industrial engineer to measure displacements needed for both directions residual stress profiles taking no longer to 50 minutes for both specimens.

The modified Layer Removal Method consist of the following steps:

- I. Coupon clamping.
- II. Layer removal.
- III. Coupon un-clamping on one side.
- IV. Displacement measurement.
- V. Step I again.

After layer removal it is recommended to wait until the specimen cool down from some heat induced during cutting, some lubrication is also recommended, this is with the propose to have more accurate displacement measurements. It is suggested to use an IP 65 sensor in order to withstand any oil. The accuracy of the probe, which was used, is $0.07 \mu\text{m}$, its resolution less than $0.01 \mu\text{m}$ and its range 20 mm. When machining, feed per tooth parameter should be below of 0.05 mm/tooth in order to avoid machining induced residual stress during the process.

Only a deflection probe is used for material characterization. The current Layer Removal method uses both deflection probe and strain gauge, however, strain gauge requires certified and qualified skills and it is too sensitive for industrial environments. Previous benchmark work shows a good agreement between results from linear probe and strain gauge.

Data Processing

After displacement measurement, the industrial engineer has to convert this data to residual stress data point with a developed analytical elastic model. Once obtained the residual stress data point, these discrete residual stress values are used to have a complete residual stress profile as a function of the thickness; An script was developed to fit from the discrete residual stresses values to a cosine function described below:

$$\sigma = c_0 + \sum c_n * \cos(2\pi * n * \xi) [MPa], \quad n = 1 \text{ to } 5 \quad (1)$$

In this equation, σ is the residual stress, ξ is the normalized through-thickness coordinate of the plate going from 0 (at the bottom of the plate) to 1 (at the top surface).

This sum-of-cosine equation was selected because it describes with high accuracy most of the residual stress profiles, it also enforces symmetry about the mid-thickness plane. Normality of the residuals is checked, as well as static equilibrium of the fitted stress functions. This tool find the best quality data in a large number of measurement datasets and fit the average residual stress profile of that data cloud. The output of this script is 6 coefficients which represents the above cosine function which will be used in the next steps. Figure 46 shows the fitted cosine function from measured data with some upper and lower margin due measurement uncertainty. Figure 47 shows the residual stress cosine functions in L and LT direction as a function fo thickness (z) [$\sigma^L(z)$ and $\sigma^{LT}(z)$].

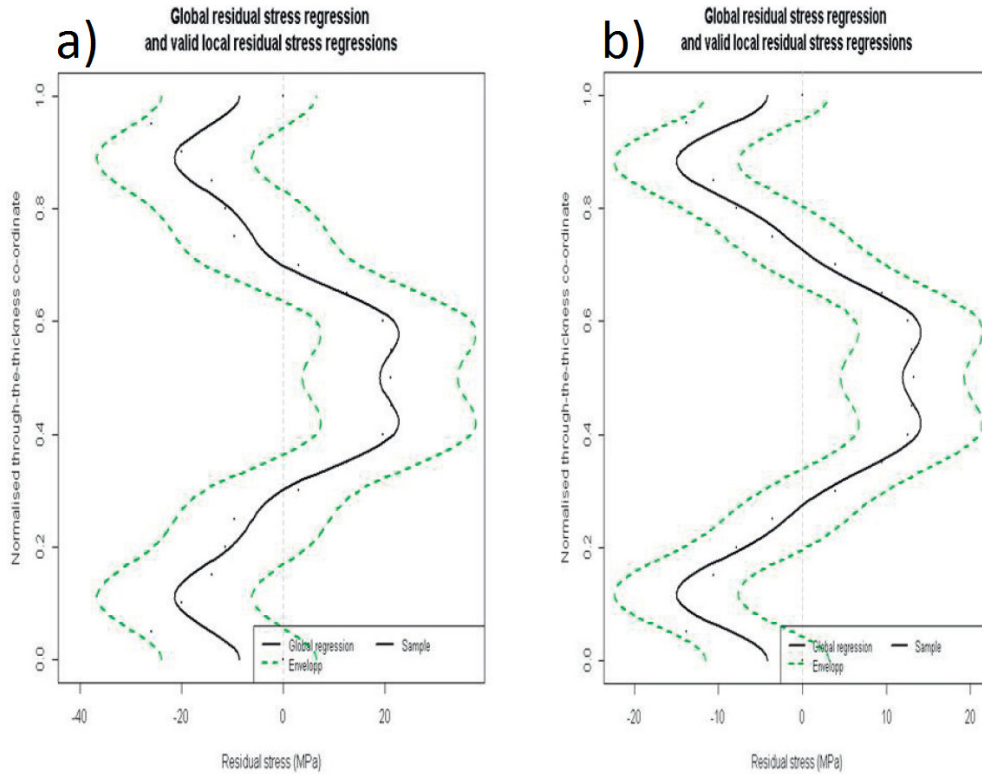


Figure 46: Cosine Fit Residual Stresses profiles in L (a) and LT (b) direction. [11]

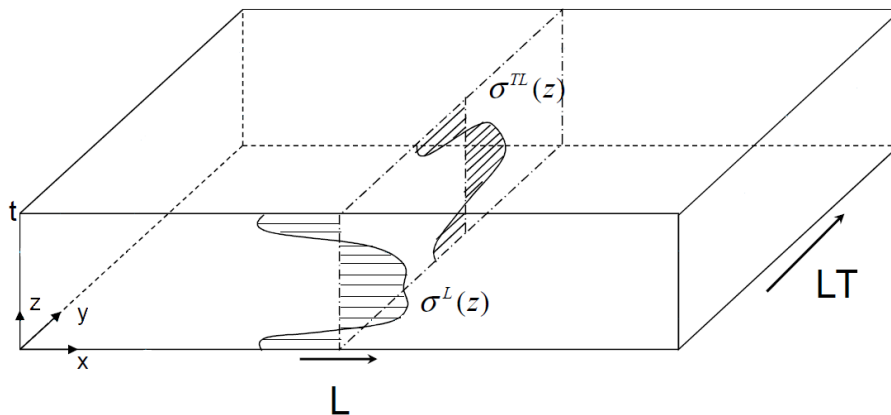


Figure 47: Schematic plate with residual stress profiles in L and LT direction as function of thickness (z).

FEM Simulation

Distortion can be categorized as in-plane and out-of-plane distortion. Reference [3] shows an analytical model using plate theory to demonstrate the influence of residual stress profiles on distortion. "The plate theory demonstrated that moment (M) is a function of the residual stress profile and the part dimension of the component, and distortion (w) is a function of the moment-induced by residual stress and materials properties". Figure 48 shows this relation between residual stresses and deformation, equations below are taken from [3].

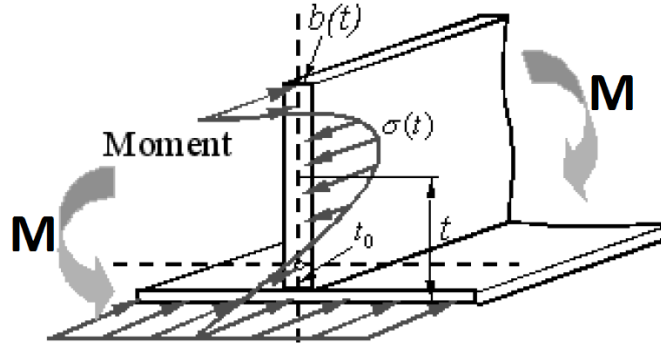


Figure 48: Simplified T-section. [3]

$$M = \int (t - t_0)b(t)\sigma(t)dt \quad (2)$$

$$w(x, y) = \frac{M_{xx}x^2}{2D_{xx}} + \frac{M_{yy}y^2}{2D_{yy}} \quad (3)$$

Knowing the residual stresses from bulk material, it is possible to predict distortion with finite element simulation. The part is located into the plate, acquiring the residual stresses from the plate, Figure 49 shows the schematic representation of part positioning into the plate with characterized residual stress profiles L and LT.

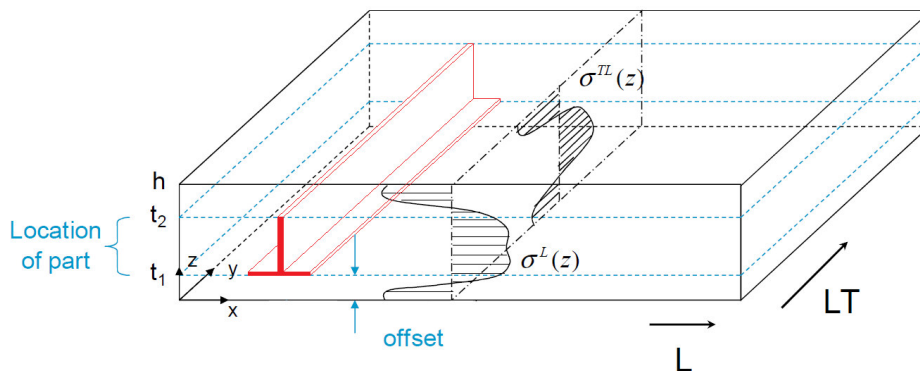


Figure 49: Schema of part positioning into the plate with characterized residual stress profiles L and LT.

The outcome of these simulations is an optimized part location into the rolled plate for minimal distortion. Figure 50 shows the schematic for optimal position in a rolled plate.

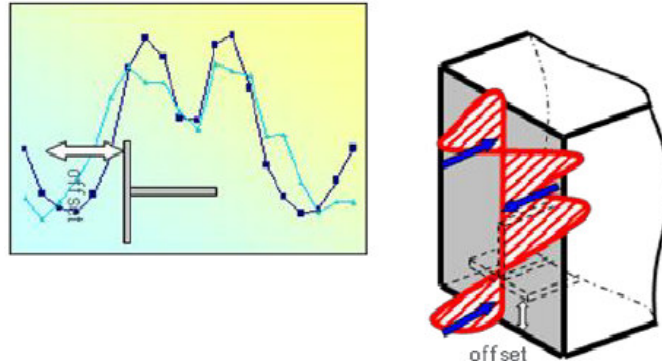


Figure 50: Part location into the mother plate. [11]

The required inputs from user are:

1. Poisson ratio (ν) and Young's Modulus (E) of the material.
2. Dimensions of the billet.
3. Residual stresses fitting coefficients.
4. Offsets range.
5. Meshed model of the examined part.

It is assumed that residual stresses are homogeneous in the plane of product, meaning that residual stress profile at the end of the plate would be exactly the same as the other end. This is generally true for rolled plates but not also for forgings. The software supports second order tetrahedron elements, these elements may not give the best results in terms of accuracy but make the entire system more efficient and pragmatic.

The workflow is developed in FreeCAD, an open source 3D CAD environment. CalculiX is used for simulation solution, it is an open source finite element solver, together with an in-house developed script. This gives the required flexibility which is needed to encapsulate the code into a user interface, tailored to shop-floor use. Post processing modules of the software gives good 3D representations of the results and summarized graphs. The simulation can be performed remotely on a centralized transnational high performance grid of computers and use up to 8 processors simultaneously. An average computational time for one large monolithic aerospace component such as panels, spars or stringers with 1 million elements and 10 different offsets, is about 20 minutes. Figure 51 shows the general diagram of the workflow proposed for distortion optimization.

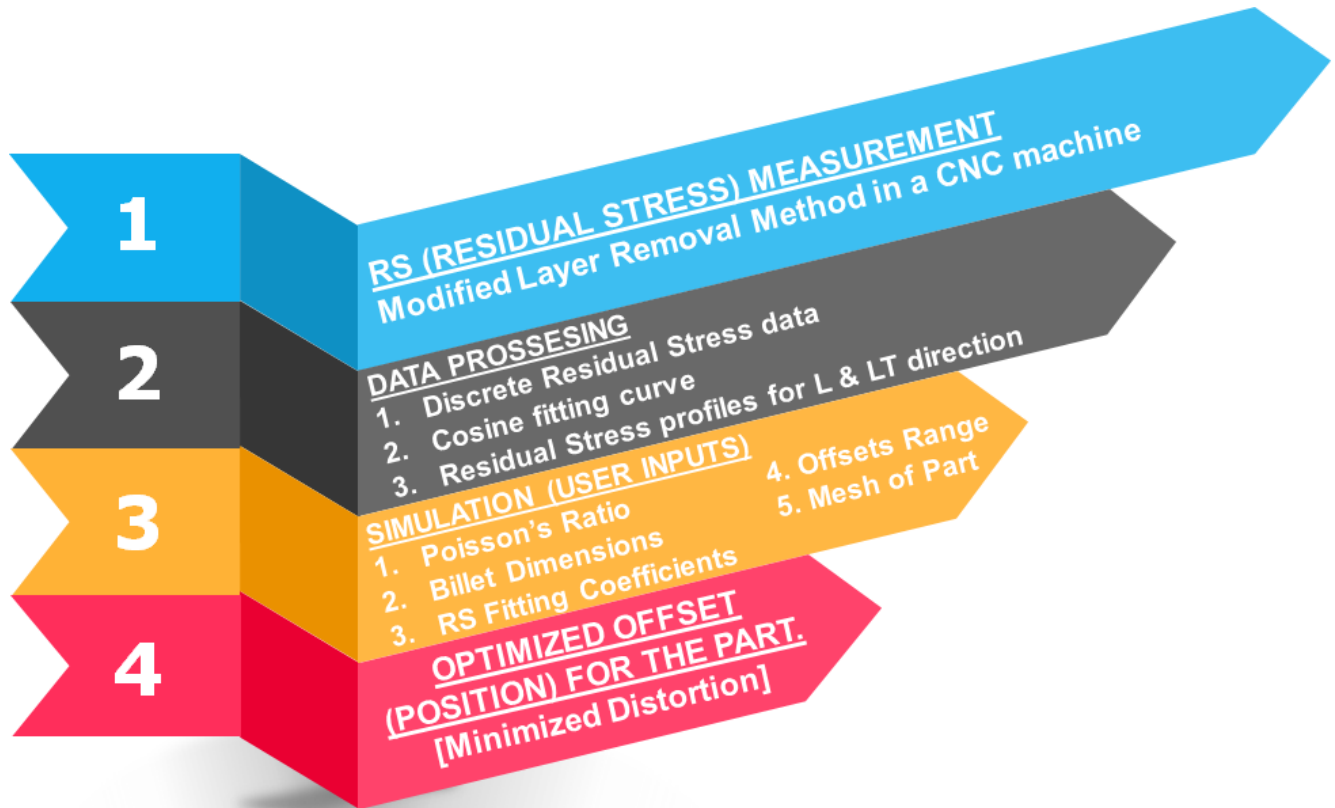


Figure 51: Proposed Workflow for minimized distortiton.

IV Software Implementation

This chapter pretends to describe the steps and processes behind the software developed for the workflow implementation in FreeCAD. This thesis work is not programming oriented; programming and development of **Part Distortion** module in FreeCAD is performed to generate the tools needed for machining distortion analysis. The propose in this chapter is not to show the text code of the software, the functions and packages used into each section of the software will be briefly described.

FreeCAD is integrated by modules that can be modified and adapted for user specifications. The programming language used in FreeCAD modules is Python. *Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. Its high-level built in data structures, combined with dynamic typing and dynamic binding, make it very attractive for Rapid Application Development, as well as for use as a scripting or glue language to connect existing components together. Python's simple, easy to learn syntax emphasizes readability and therefore reduces the cost of program maintenance. Python supports modules and packages, which encourages program modularity and code reuse. The Python interpreter and the extensive standard library are available in source or binary form without charge for all major platforms, and can be freely distributed.* [23]

FreeCAD Workbenches

Workbenches are group of tools (toolbar buttons, menus, and other interface controls) that are grouped together by specialty. Think of a workshop where you have different people working together: A person who works with metal. another with wood. Each of them has, in their workshop, a separate table with specific tools for his/her job. However, they can al work on the same objects. The same happens in freeCAD. [15]

The Mod folder in FreeCAD installed location contains all the workbenches; every time FreeCAD is open all the workbenches are loaded.

Part Distortion Workbench

Into Mod folder into FreeCAD installation location, a folder called **Machining_Distortion** contains the files for **Part Distortion** workbench. These scripts were taken from FreeCAD source page <http://free-cad.sourceforge.net>, made by **Juergen Riegel**. The scripts were improved and adapted to required functionality of the FreeCAD software. Each section of the **Part Distortion** workbench has its own script, interacting all together when the workbench is running.

Qt is used for software interface in FreeCAD; Qt is a cross-platform application framework that is used for developing application software that can be run on various software and hardware platforms.

The **Machining_Distortion** folder contains files in different formats, Python (.py) files, Compiled Python (.pyc) files and Qt Ui (.ui) files. There is also a folder called **DOE**, where the info required for the two levels, fractional factorial designs is located.

Every workbench module in FreeCAD must contain an Init.py file, which indicates that the folder contains a workbench.

Add Part

The **Add Part** section is based on **Machine-Distortion Mesh managment** file from the web-page and author previously mentioned. This module open a navigator to select a valid format mesh or part (.bdf, .unv, .med, .dat, .stp, .igs) and load it into the freeCAD **Part Distortion** workbench. Next Qt function is called.

`QtGui.QFileDialog.getOpenFileName()`

Depending on the type of file loaded, FreeCAD will open the **Part** or **Fem** modules to start working, if a part file is loaded, the internal tools of freeCAD will let the user generate a mesh from the loaded part, then the **Part Distortion** workbench will start to set up the analysis. If a mesh is selected, the **Part Distortion** workbench will directly start with the set up of the analysis.

Part Alignment

The **Part Alignment** section is based on **Machine-Distortion Alignment management** file from the web-page and author previously mentioned. The GUI and script were improved to increase functionality and user capabilities. The object (mesh) is placed into the positive octet of the space coordinates, it can be oriented with the next function.

`object.Rotation.multiply(FreeCAD.Rotation(FreeCAD.Vector()),angle))`

The improved script lets the user to flip 90° in any axis, or go further and rotate with an specific angle, giving the user all the flexibility and capability to position the meshed part following the specifications.

Material Fit

The **Material Fit** section is based on **Machine-Distortion Material fit and plot management** file from the web-page and author previously mentioned. The GUI and script were improved to increase functionality and user capabilities, focusing on material variation analysis. The developed section lets the user to design experiments for 2 levels fractional factorial designs. Subsequently R tools for design of experiments analysis are used to report the main and coupled effects of the residual stress coefficients.

The coefficients can be modified all at the same time in an specific amplitude or they can be modified independently with different amplitudes for each coefficient. For design of experiments analysis, at least 2 coefficient must have an amplitude, generating a full factorial design (4 experiments), increasing the number of variables the number of experiments increases in the way 2^k ; fractional design are needed for main and coupled effects, reducing considerably the number of experiments.

The script was improved including the possible designs depending on the number of variables and amplitude for the specific user requirements, a folder with 50 files contains 25 .txt files with the design information and 25 .cvs files with the combinations of the two levels for each variable required. The design information is shown into the FreeCAD interface, the .cvs file is used once the design has been chosen to create the input files with the specific variation of the coefficients.

Machine-Distortion Isostatic

The **Machine-Distortion Isostatic** section is based on **Machine-Distortion Isostatic management** file from the web-page and author previously mentioned. This script was not modified, it call internal functions to identify the closest node to coordinate (0,0,0), the closest node to coordinate (length,0,0) and the closest node to coordinate (0,width,0). These nodes are used for boundary conditions in isostatic analysis.

Generate Jobs

This is the most important script of the module, it generates the input files for analysis depending on the information captured by the other sections. The **Generate Jobs** section is based on **Machine-Distortion Analysis management** file from the web-page and author previously mentioned. The GUI and script were improved to increase functionality and user capabilities, it is adapted to the modifications made by the other sections, ensuring the correct interaction and functionality between the scripts, taking specific care into the variables names and characteristics. Any change in a script must be considered by the other scripts, otherwise the software will have complications when running.

The section ask the user for the positions required for the analysis, rotations through X, Y and Z axis are permitted, translation in Z is permitted as well (translation in the other axis make no changes into the simulations). The section also ask for an specific position in which the 2 levels fractional factorial design will occur.

Generate Jobs section concentrate all the information from previous sections to include it into the input file for the analysis, an unique input file is generated with the mesh information, transformation nodes, the material properties, the boundary conditions etc. A folder containing a .txt file is generated for each position or experiment int he case of DOE analysis; this file contains the coefficient for each residual stress profile (L and LT direction) and the matrix of transformation containing the specific position required by the user.

The specific position and orientation is defined by an affine transformation, modifying the coefficients of the 4x4 affine transformation matrix:

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The r coefficients represents rotation through the three axis and t coefficients represent translation through the three axis.

Read Results

The **Read Results** section is based on **Machine-Distortion Postprocessing** file from the web-page and author previously mentioned. The GUI and script were improved to increase functionality and user capabilities, including the Design of Experiments section, developed into this thesis work. The script was improved to read the .frd result files after simulation in CalculiX, holding the minimal and maximal displacement into the X, Y and Z direction and generating a .csv file with the relevant information for each simulation. The script generates two .csv files, one for positioning analysis and the other one for DOE analysis.

The interface was upgraded, including a progress bar at the bottom of the FreeCAD environment. This is useful for heavy simulations where reading results time is longer than light simulations; it also helps when the number of simulations is very high, the progress bar shows the remaining time to finish the task.

Report Results

The final section is **Report Results**, is totally developed by the author of this thesis work. In this script, an R file is generated for results visualization. In the developed interface, the user can select the kind of results depending on his interest.

This R code reads the .csv files which contain the summarized results from simulations. The R code generate the required plots and insert them into a .pdf file.

For the 2 levels fractional factorial design, default plots are added to the report (frequency, density, norm quantiles, box-plot, main effects plot, interaction plot matrix, half normal plot $\alpha = 0.1$)

V Case Study

The main objective of this thesis work is to implement the proposed workflow in Reference [11] developing an integrated and efficient software module, which permits to follow the steps in an friendly software environment, easy to handle by an engineer at the shop floor level. FreeCAD-CalculiX-R open source softwares were modified, adapted and integrated for this propose.

The best way to show the capabilities of the software developed is through a case study, where the interface and functionalities of the software developed are exposed through a representative case, which can be validated at the shop of the University of Guanajuato. Aluminum Alloy 7050 T-7451 is used for the analysis.

The project is not programming oriented, the objective of this thesis work is to develop, integrate and implement the software needed to follow the workflow; there is not special interest into the structural integration of the programming code but in the functionality and interface of the software.

Representative Geometry

A representative geometry is designed in order to measure the capabilities of the FEM software and its accuracy predicting distortion through the defined workflow. Structural components located at the wings of the aircrafts are usually machined from rolled plates (panels, spars, stringers or ribs). Figure 52 shows an schematic diagram of structural components at the wings of the aircrafts.

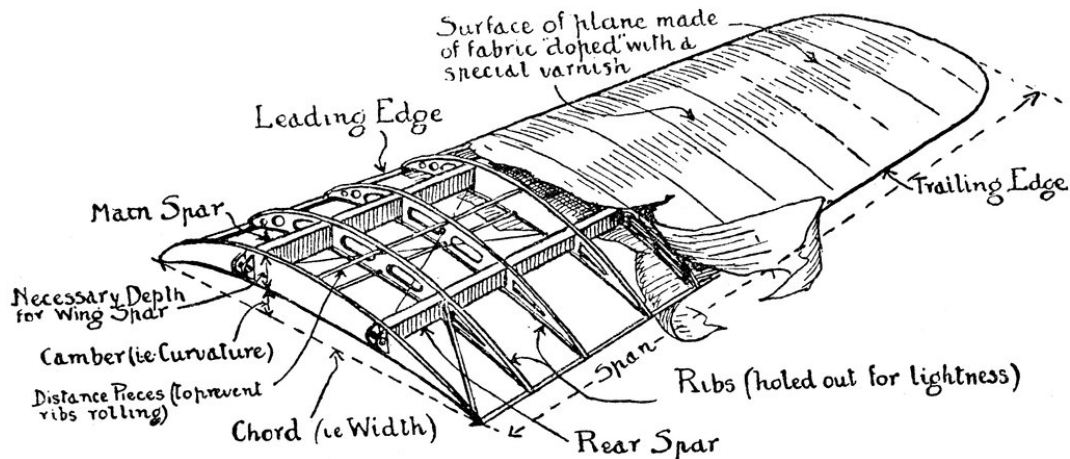


Figure 52: Airplane wing diagram (schema). [20]

An important internal part of the wing are the ribs, which provides support to the structural wing, these structures are machined to thin complex shapes and holes reducing mass as much as possible. Figure 53 shows a typical rib located internally into the wings, most of the material is removed to an optimal structural support component.

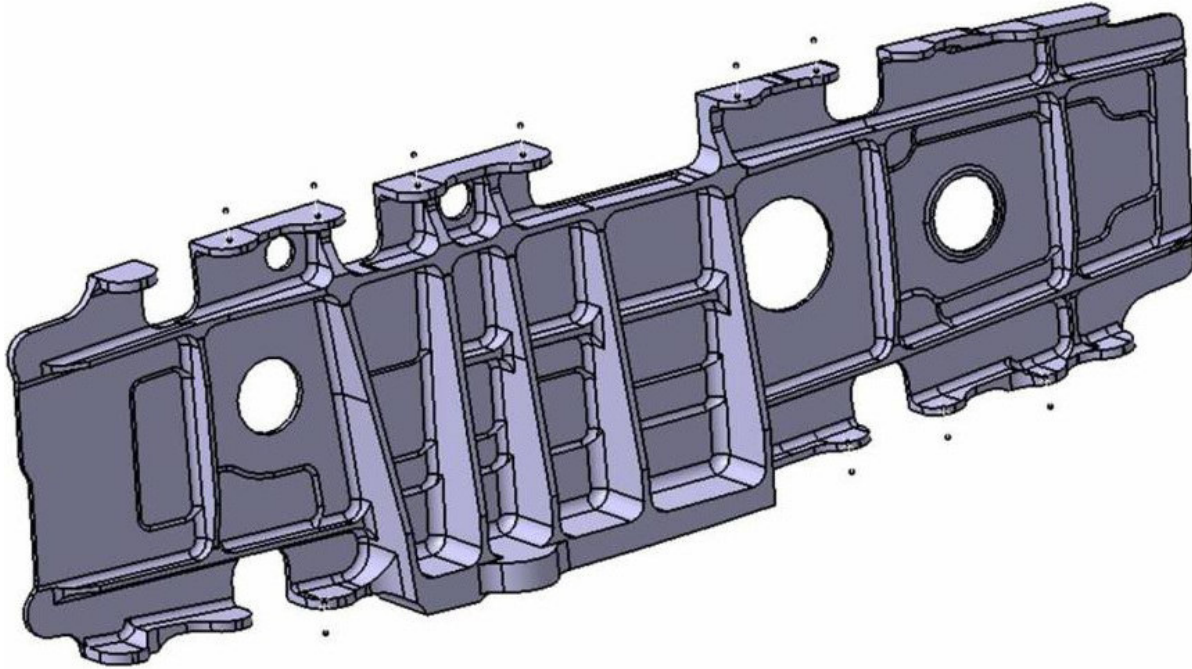


Figure 53: Airplane wing diagram (schema). [19]

Due the large dimensions that this elements can have in big commercial aircrafts, distortion when machining can vary from 3 to 15 cm or even higher, this distortion is difficult to repair because this elements are assembled sideways, the smallest deviation complicates the assembly because the bolts with not have coincidence to the rib drilled lateral holes. Figure 54 and Figure 55 shows some photos of this structural component.



Figure 54: Wing with assembled ribs. [19]



Figure 55: Internal view of the aircraft wing. [19]

The CNC center located at the University of Guanajuato workshop has dimensional limitations, for subsequent validation after simulation, a (400x400x50) mm plate is supposed to be machined, a rib with length 400 mm, width 400 mm and thickness 40 mm would be machined into this plate. Figure 56 shows this typical rib structure, representing the structures used in aeronautics for wings structural support. A detailed draw with dimensions of the proposed geometry that is used for simulation is attached at Appendix A.

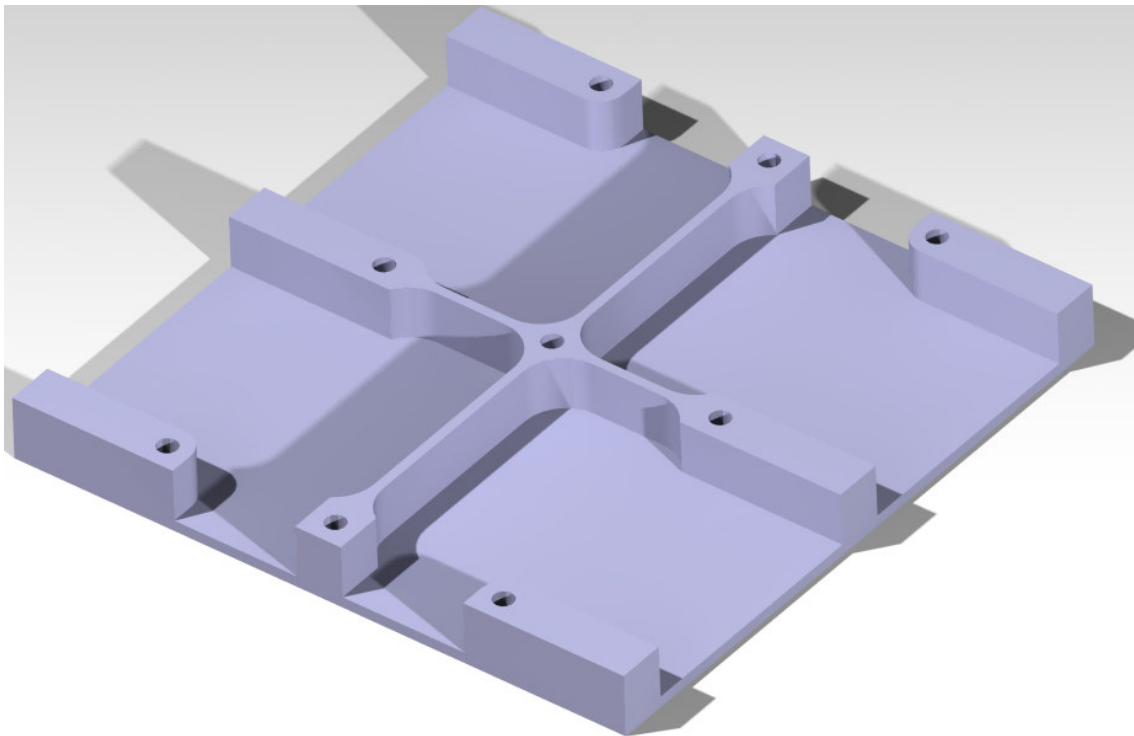


Figure 56: Representative rib geometry.

FreeCAD Pre-Processing

After having defined the structural part, the simulation process starts, the developed FreeCAD module is explored describing all the characteristics and tools. When opening FreeCAD, the home interface shown in Figure 57 appears.

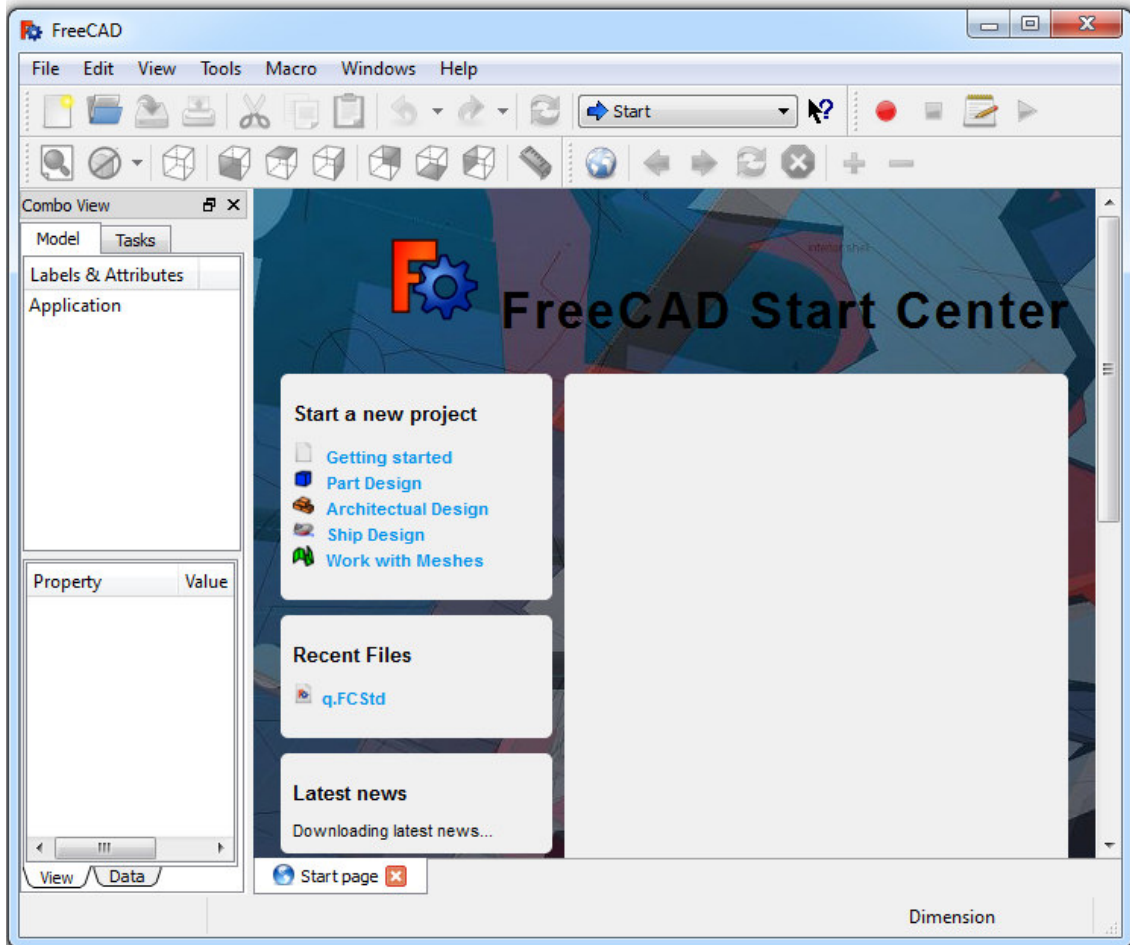


Figure 57: Initial FreeCAD software interface.

As any other software, a menu bar is seen at the top (File, Edit, View, Tools, Macro, Windows, Help), followed by a standard tool bar (new, open save, print, cut, copy, paste, etc.) the module selection is located at this bar. The next bar has view controls. The central area is the graphic zone, similar to any other CAD software, draws and elements are visible at this area. Current model options and task for each module are shown at the left. To start with the machining distortion analysis, the Part Distortion module must be charged, Figure 58 shows where this option is located.

After opening the Part Distortion module, the interface shown in Figure 59 will appear; at the Tasks menu in left, there is a Start menu with Machine-Distortion Analysis as option, it must be selected in order to start machining distortion setup.

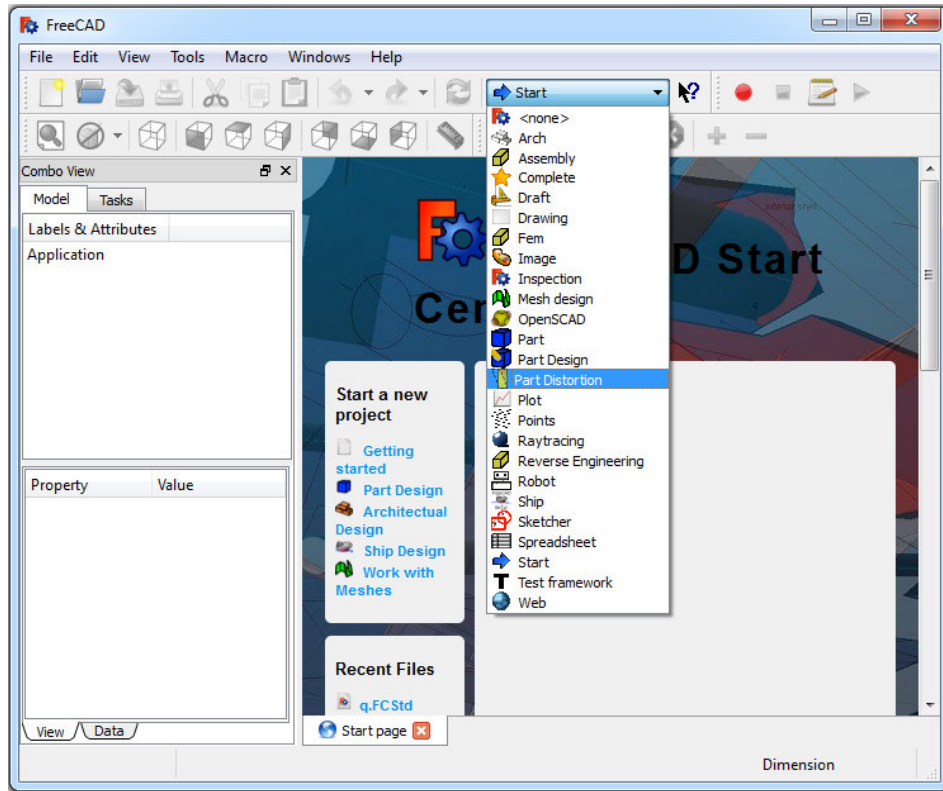


Figure 58: Charging the Part Distortion module in FreeCAD.

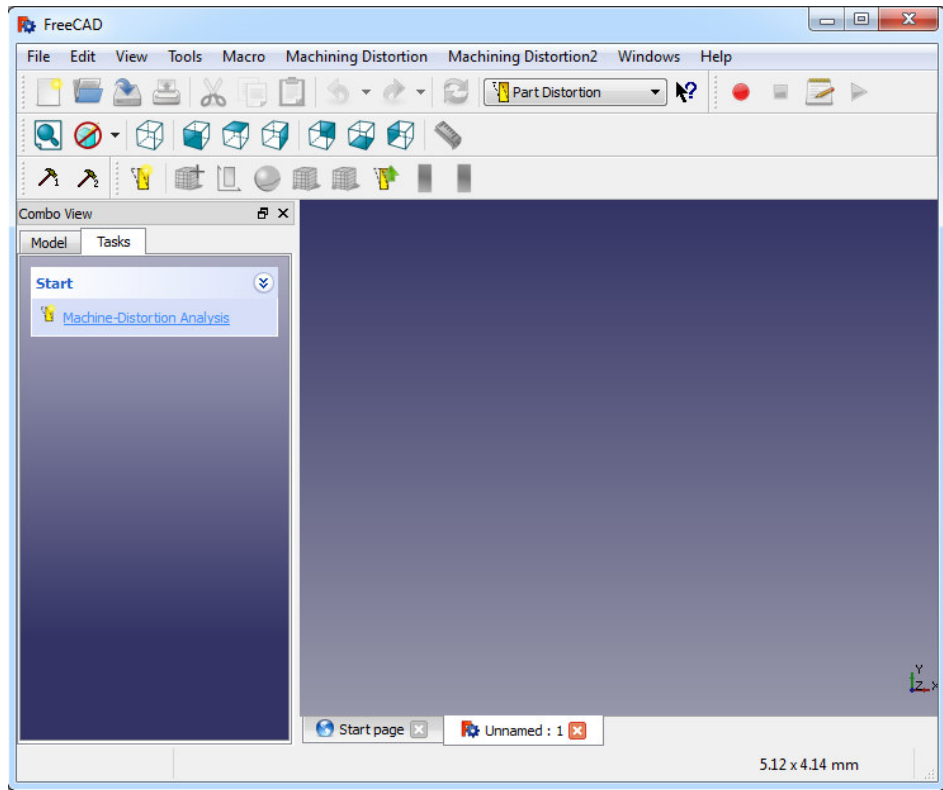


Figure 59: Initial interface of Part Distortion module.

Once Machine-Distortion Analysis is selected, the sequential menu is displayed at the Tasks area on the left, starting with Add Part, then the geometry is positioned with Part Alignment tool, once aligned, material information is added (residual stress profiles and mechanical properties of the material used), then the user select between Isostatic or Ground analysis, the final step is to generate the input files with positioning variation.

Once having the results from CalculiX, the .frd result files are read for final summarized results. Figure 60 shows this initial menu.

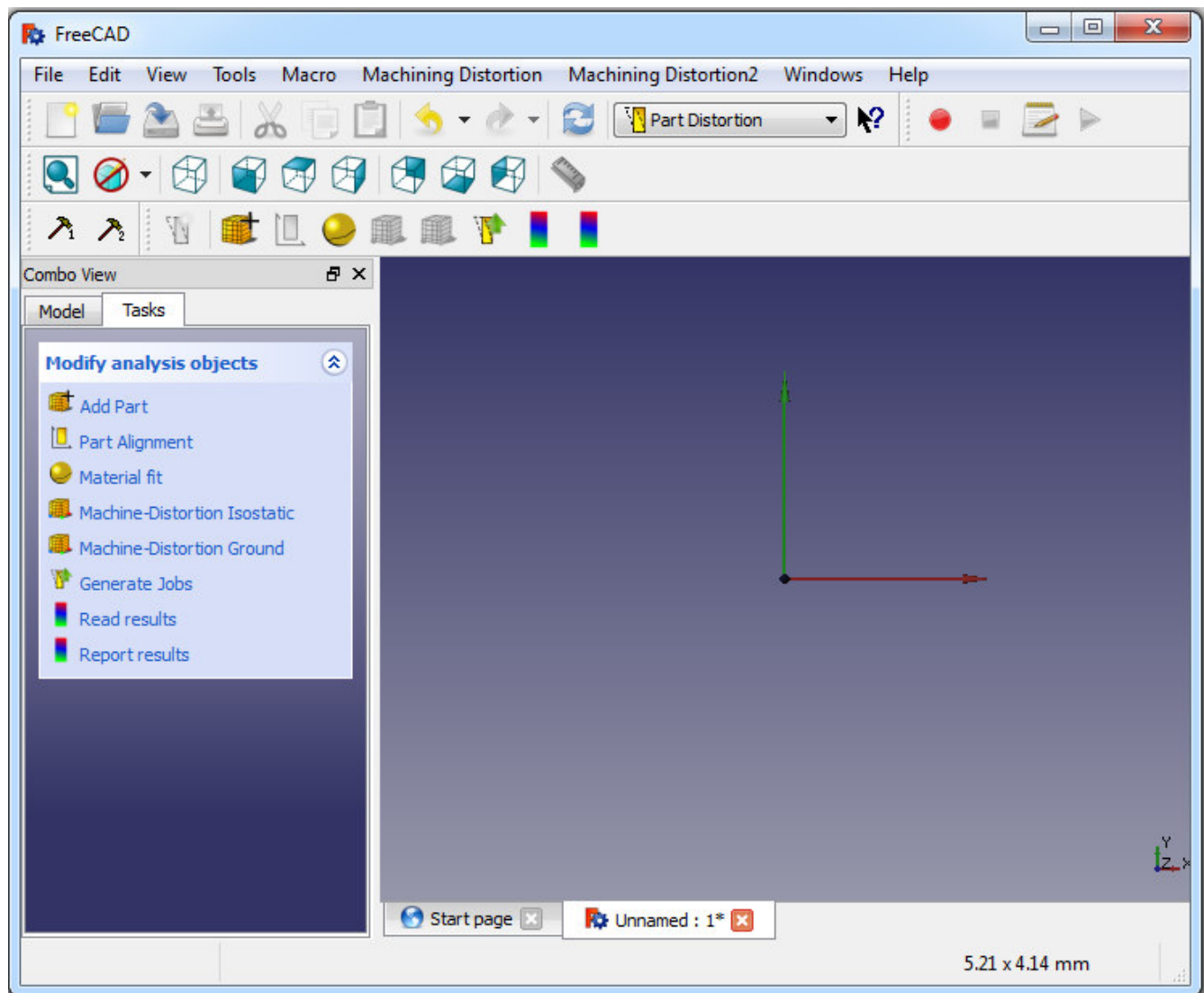


Figure 60: Sequential options for machining distortion analysis.

Meshing & Input

The part geometry can be generated and meshed in FreeCAD before running the Part Distortion module, however if better mesh tools in external software are available, it is strongly recommended to use them (Catia, Abaqus), Gmesh is another open source very useful for good mesh. If mesh is imported, second order tetrahedron elements in long-format (.bdf) file is easily handled by FreeCAD. When clicking at **Add Part** option, an Open File Dialog Window appears, ready to find and select the .bdf mesh file. For this case study, 3mm second order tetrahedron elements mesh is generated in Catia, then exported in .bdf long-format. Figure 61 shows the generated mesh. Figure 62 shows the FreeCAD interface once mesh has been imported.

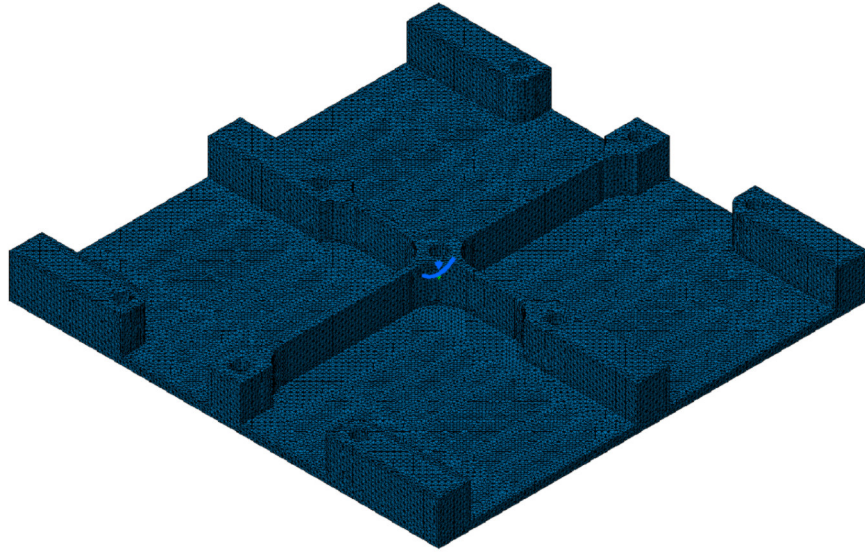


Figure 61: Second order tetrahedron elements mesh generated in Catia.

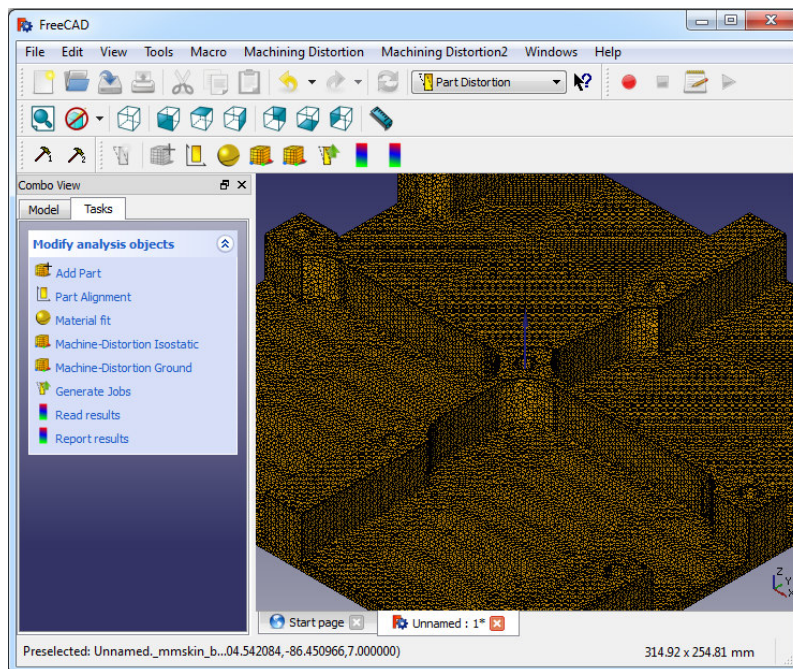


Figure 62: Mesh imported to FreeCAD Part Distortion module.

Alignment of the Geometry

The **Part Alignment** tool lets the user to position the part in the 3 axis spatial system, locating the part by rotating it 90deg about the X, Y or Z-axis. This tool reduces the bounding box, optimal reduction of this hypothetical box can be done automatically when flipping or a final optimization can be done when pushing **Minimize** button. The volume menu gives important information about the bounding box at the specific position, in this case it shows 400 units length, 400 units width and 40 units of thickness which coincide with the representative geometry. The last part of the menu gives more control about the positioning of the part, letting the user to rotate specific degrees in any axis.

It is very important to do this initial positioning not only to reduce box bounding, but also to set how residual stress profiles will be applied, taking into account that L residual stress profile will be mapped at X direction, and LT residual stress profile will be mapped at Y direction. It may not be clear the functionality of this tool for the representative geometry because it is flat at the bottom, but for more complex geometries, **Part Alignment** tool is very useful.

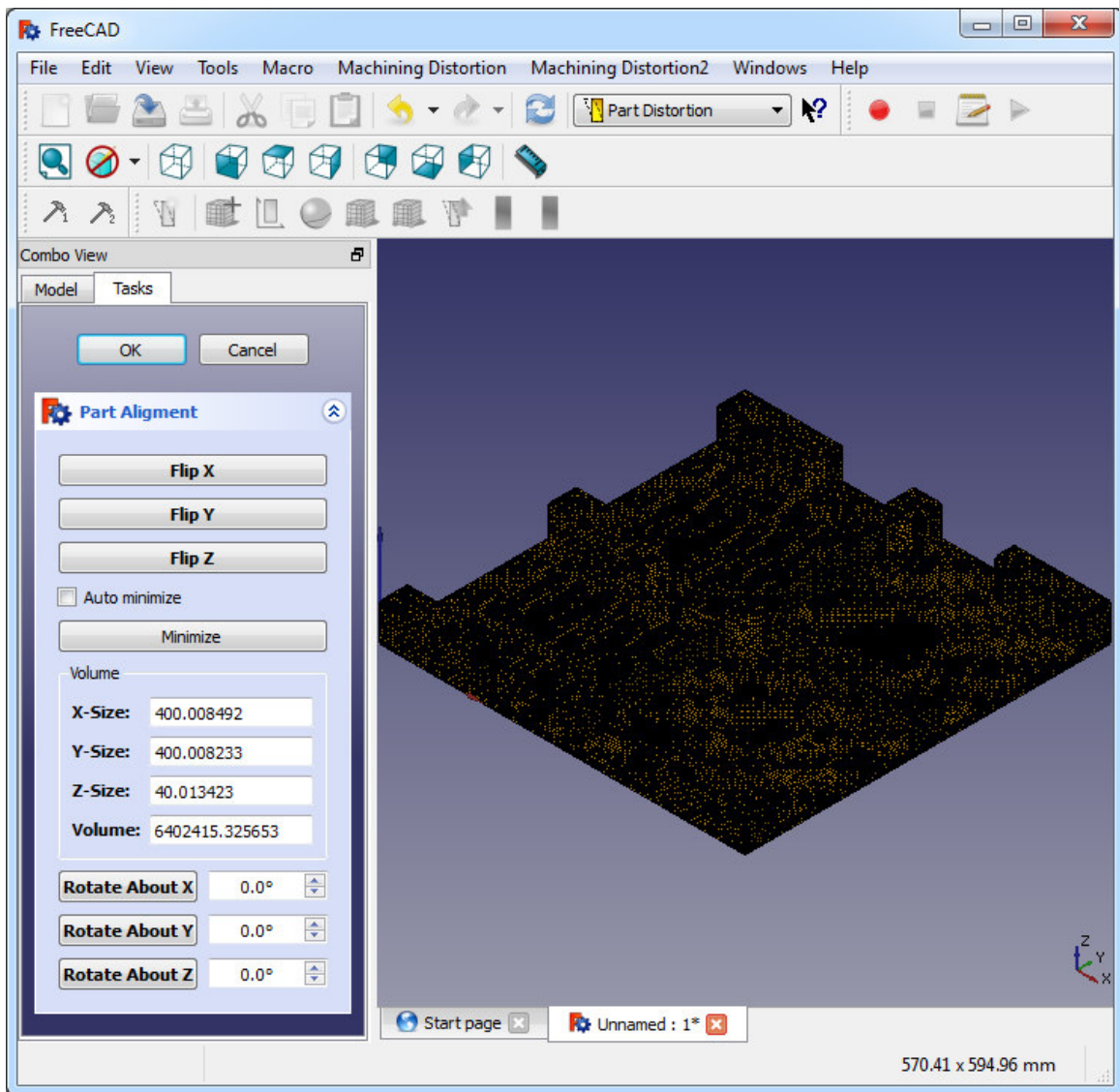


Figure 63: Part Alignment menu at FreeCAD.

Material Properties

The **Material fit** tool is designed to manually introduce or load the material properties, inputs needed for distortion simulation (young modulus (E), Poisson's ration (ν)). Next to Material information, there is a section for plate dimensions (thickness, width and length), default values are generated based on the part dimensions in order to reduce Buy to Fly ratio, increasing material dimensions will update this value defined as:

$$\text{Buy-to-Fly ratio} = (\text{length}_{\text{min vol bounding box}})(\text{breadth}_{\text{min vol bounding box}})(\text{plate thickness}) \quad (4)$$

The final section of this menu is the residual stress configuration, where residual stress profiles for both L and LT directions must be manually introduced or charged from a .txt file (general format of this file can be consulted in Appendix B). Figure 64 shows the interface for material menu, some extra features can be seen in residual stress configuration section.

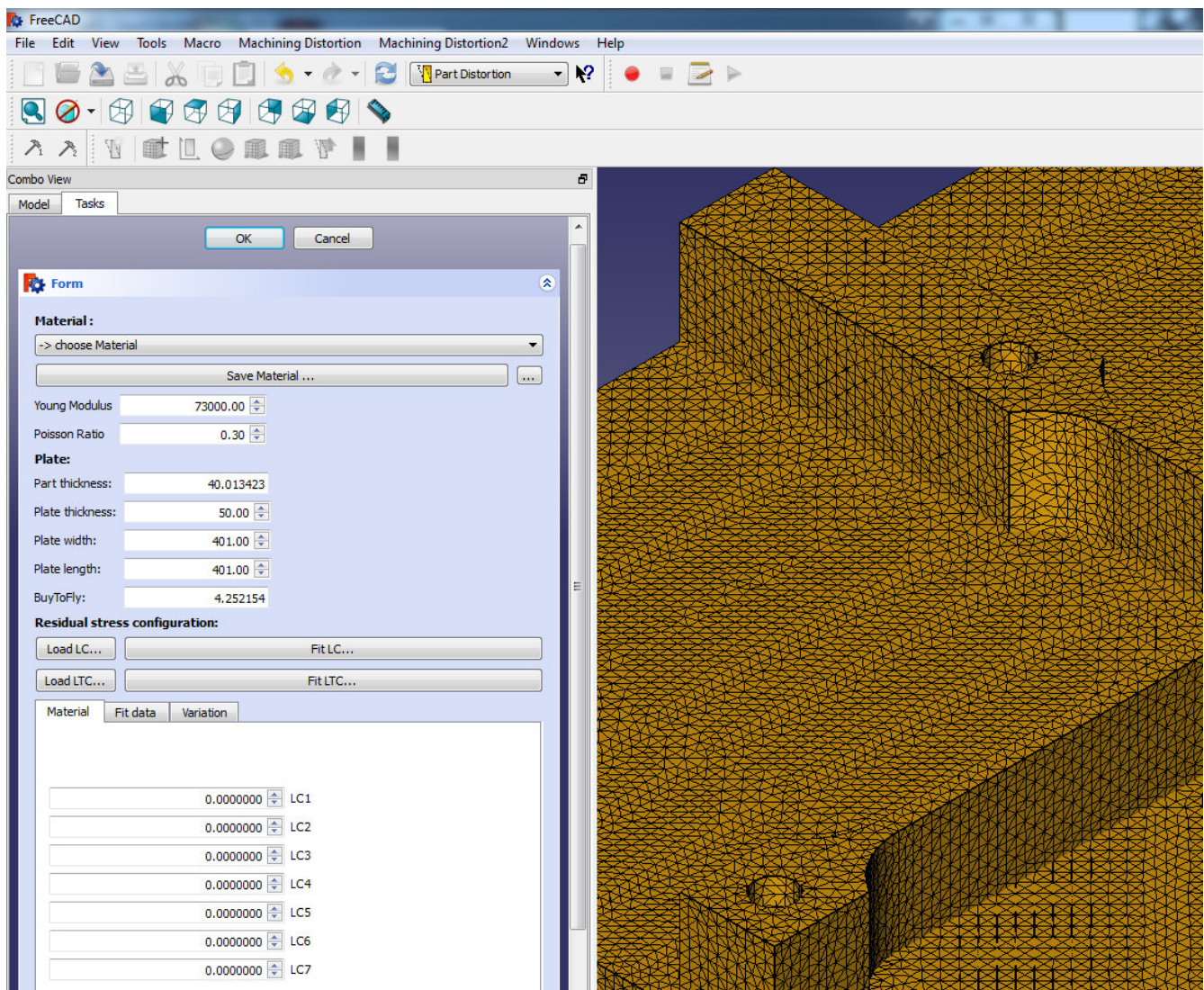


Figure 64: Material menu at FreeCAD.

The **Residual stress configuration** section lets the user to charge a .txt file where the six coefficients described in equation (1) are saved, these coefficients can be directly introduced. A .csv file can be loaded with residual stresses measurements, fitting the data to the equation (1), auto generating the coefficients, **Fit data** tab shows the fitting information. The last tab in this section, **Variation**, was designed to perform residual stresses influence in results, letting the user know the robustness of the simulation results.

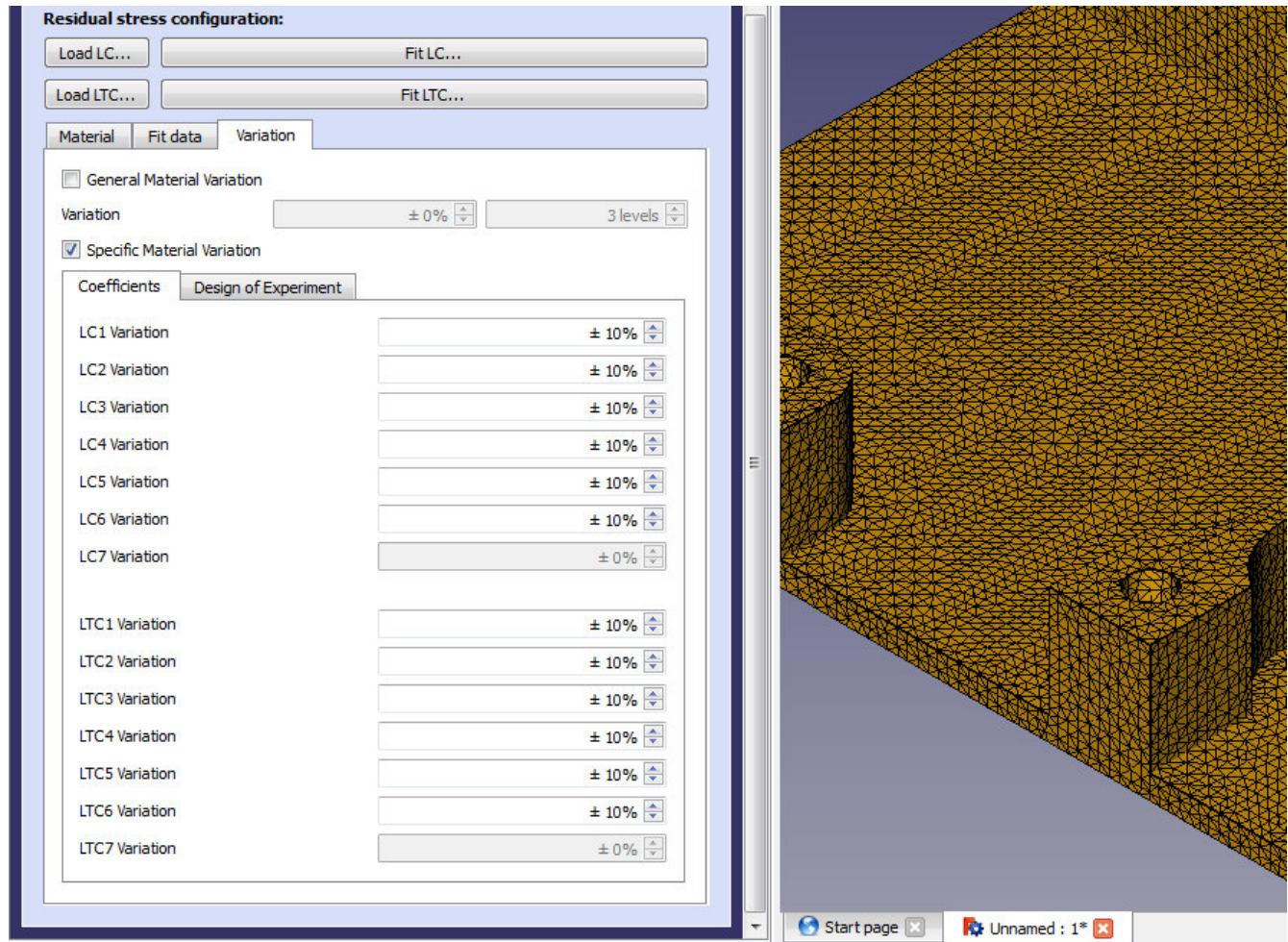


Figure 65: Material menu (Residual Stresses) at FreeCAD.

The **Variation** tab has two sections that can be activated after charging the residual stress coefficients for both directions. The first section is to include general material variation to the analysis, this will vary all the coefficients at the same time a desirable percentage with a number of levels. 10% variation in 3 levels means that for each position analysis, it will generate three simulations, one with 90% the value of the coefficients, another with 100% the value of the coefficients (no change), and the last one with 110% the value of the coefficients. If the number of levels increases to 5, the number of simulations for each analysis will increase to 5 having the next coefficient configuration (90% first, 95% second, 100% third, 105% fourth, 110% fifth), same range of coefficient variation but more simulations by positional configuration.

Independent variation for each coefficient can be performed in the second section, only the charged coefficients can be analyzed, going from one coefficient analysis to 12 coefficient analysis.

The number of coefficients with variation are the number of factors to perform into a two levels fractional factorial experiment design, determining the sensitivity and influence of each coefficient independently. Once selecting the coefficients and its amplitude, the **Design of Experiment** tab will show information about the experiment to be generated, specifying general experiment information depending the fractional factorial design selected by the user. This information is the number of experiments, the number of factors, the resolution of the design, generators for the fractional factorial design and confounding warning if some terms are confounded specifying them, finalizing with the combinatorial design going from A for the first coefficient with variation different to 0 and finalizing with M when all 12 coefficients are analyzed; this design specifies positive or negative amplitude of each factor. Figure 66 shows this information in the FreeCAD interface.

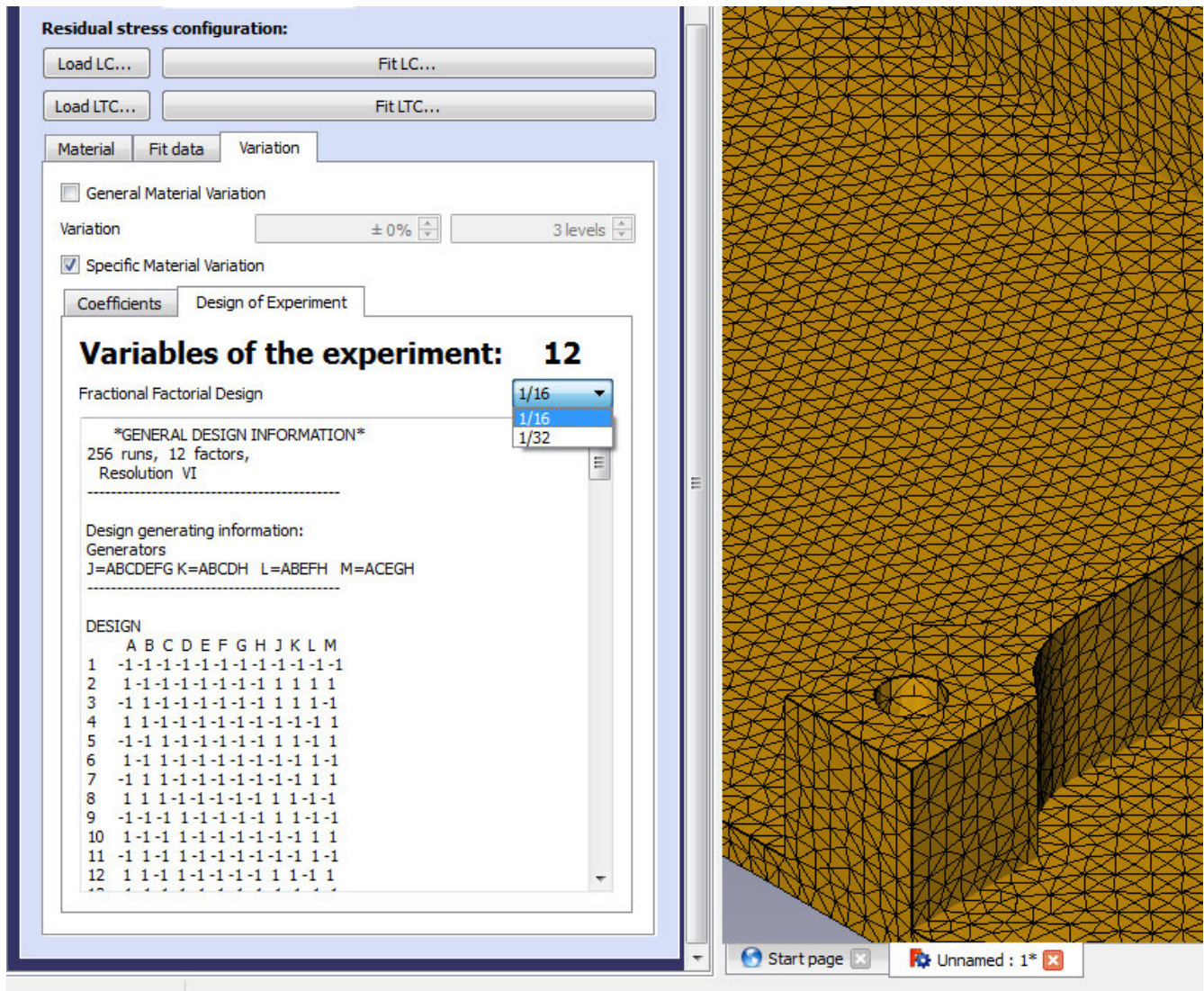


Figure 66: Design of Experiments menu at FreeCAD.

Appendix C shows the possible experiments configuration depending on the number of coefficient with variation and the fractional factorial design. This information is taken from R Design of Experiments package (DoE.base).

Machining Distortion Isostatic/Ground

Next step is the boundary conditions set up, **Machine-Distortion Isostatic** menu automatically choose 3 points at the lower surface of the geometry, closest nodes to $(0,0,0)$, $(\text{length},0,0)$ and $(0,\text{width},0)$ coordinates, setting boundary conditions at these points; displacement boundary conditions in three directions X, Y and Z for closest node to $(0,0,0)$, displacement constraint in Y and Z directions for closest node to $(\text{length},0,0)$ and displacement constraint in Z direction for closest node to $(0,\text{width},0)$.

A local coordinate system through these three nodes is generated automatically, and the displacements boundary conditions are transformed into this coordinate system to ensure perfectly iso-static boundary conditions.

Figure 67 shows the FreeCAD interface for Machine-Distortion Isostatic menu, the three chosen points are the corners of the remarked triangle (isostatic plane), in this case nodes 80($0.0077, 0.0005, 0.0079$), 77($400.00, 0.0082, 0.0$) and 132($0.0, 400.00, 0.0134$). The decimals in this case are due the positioning of the part, this tool perform the optimal positioning but always with some small error due mesh quality.

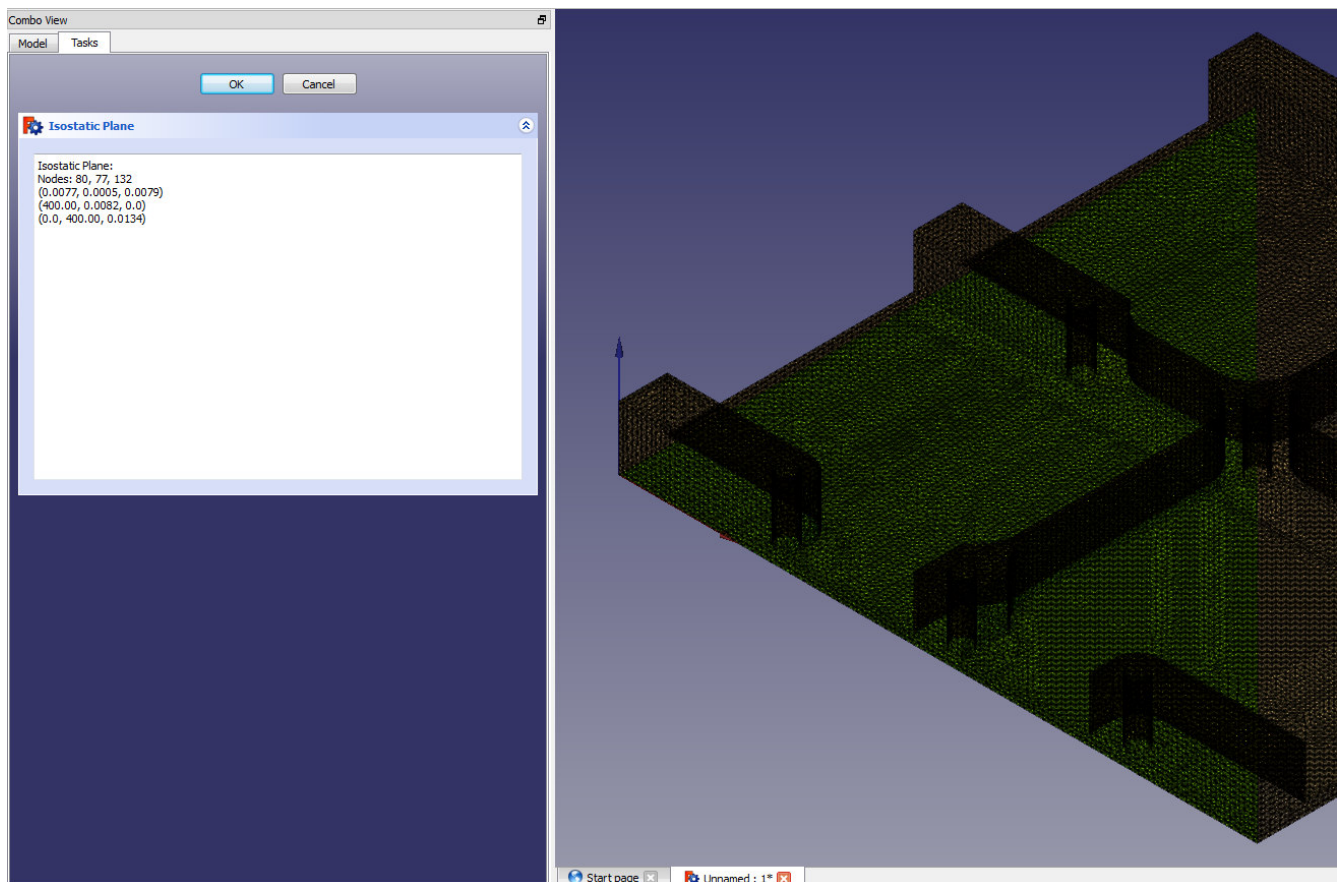


Figure 67: Machine-Distortion Isostatic menu at FreeCAD.

There are not parameters to modify on this menu, the lower surface is always analyzed taking nearest nodes to points previously described, this is very useful for complex geometries and components.

Machine-Distortion Ground menu choose 3 points at the lower surface of the geometry, closest nodes to $(0,0,0)$, $(\text{length}, 0,0)$ and $(0, \text{width},0)$ coordinates, to create a plane in order to set up ground simulations, this analysis is more complex because there is interaction between the surface of the part and surface of the plane generated, gravity influence is taken into account to perform these interactions, mass of the part may contribute to extra distortion in the solution, however, this analysis is not recommended due complexity and more resources needed to perform it.

Figure 68 shows this interface, in this case the same nodes as Isostatic analysis are chosen. In the figure it can be seen the plane generated, the triangle in green, which contains the part, situated at the bottom of the component.

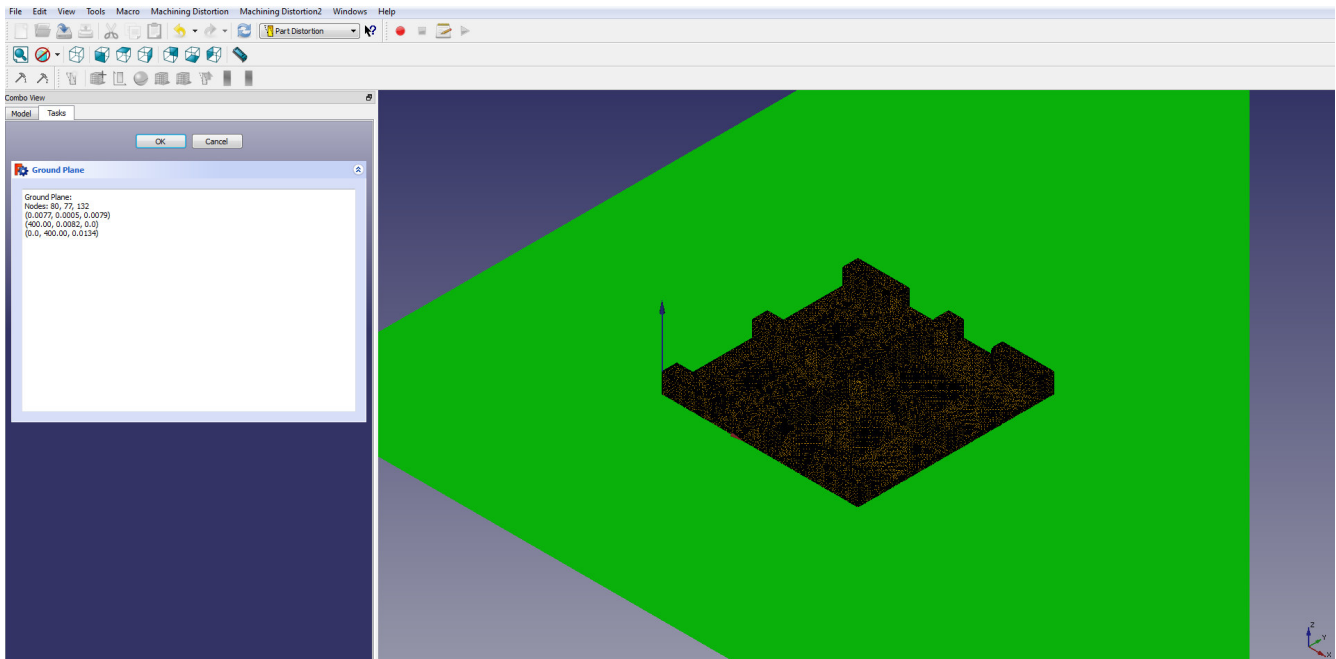


Figure 68: Machine-Distortion Ground menu at FreeCAD.

As previous menu, this menu does not have parameters to modify, it follows the same basis as previous Machine-Distortion Isostatic menu.

This section of the software is not totally developed due complexity in simulation and not big advantage in accuracy compared with isostatic analysis. Further work would be to improve this section to make it totally functional.

Jobs Input Files Generation

Final step for FreeCAD pre-processing is the input files generation for calculation by CalculiX solver, **Generate Jobs** menu has been developed to produce the input files where previous set up information will be recorded, (mesh geometry, material properties and residual stress profiles, boundary conditions), this menu requires positioning information for simulation design, the part can be positioned with four degrees of freedom (position in z and rotation about x, y and z axis) regarding the basic assumptions for the project (homogeneous residual stresses where residual stress state on one end of the plate is the same as that at the other end) making no change in simulation results when positioning in x and y directions.

The user must select the range of values for position of the part into the plate, one starting value for each parameter and one ending value to close the range, an interval value is needed to determine the number of simulations between the range values.

Figure 69 shows the Generate Jobs menu, in this specific figure, the user set up variation in the four parameters, going from 0 to 3 degrees of rotation about x axis with 1 degree interval, from 0 to 5 degrees of rotation about y axis with 1 degree interval, from 2 to 5 degrees of rotation about z axis with 1 degree interval and 0 to 3 mm Z offset with 1 mm interval, this configuration would generate an input file for each specific position combining the parameters, total number of input files would be 4(going from 0 to 3 with 1 as interval for rotation about x axis) \times 6(going from 0 to 5 with 1 as interval for rotation about y axis) \times 4(going from 2 to 5 with 1 as interval for rotation about z axis) \times 4(going from 0 to 3 with 1 as interval for Z offset distance) resulting 384 configurations for this analysis.

At the right side of the positioning options is a menu to specify specific position of the part for stress coefficients analysis, a check option is optional to generate positions out of the plate, especially when it gets out in x or y direction, for z direction it must be taken into account that results would not be accurate since out of the thickness there are not residual stress values.

A computer location must be specified in order to save the input files, a folder named "Distortion" is created at this location.

Each position configuration is shown, for outside of plate positions a warning specifying which limitation is violated (Outside Thickness-Width-Length), this warning must be considered since buy to fly value will increase with these positions, special attention when part is outside thickness, simulating this position would not make sense.

Figure 70 shows the folder in the specified location with the input files, each position in a folder (plate thickness, stress profiles and specific position is saved in each folder for each position) with two extra files, one for general set up in analysis (mesh, mechanical properties, boundary conditions) and another one to automatically run all the simulations one by one.

With the limitations at the CNC center at the University of Guanajuato, a simple study is performed, varying only the Z offset parameter, rotation into the plate would be more complex to machine at the work shop. 11 cases are analyzed going from 0 to 10.5 mm (0, 1.05, 2.1, 3.15, 4.2, 5.25, 6.3, 7.35, 8.4, 9.45, 10.5).

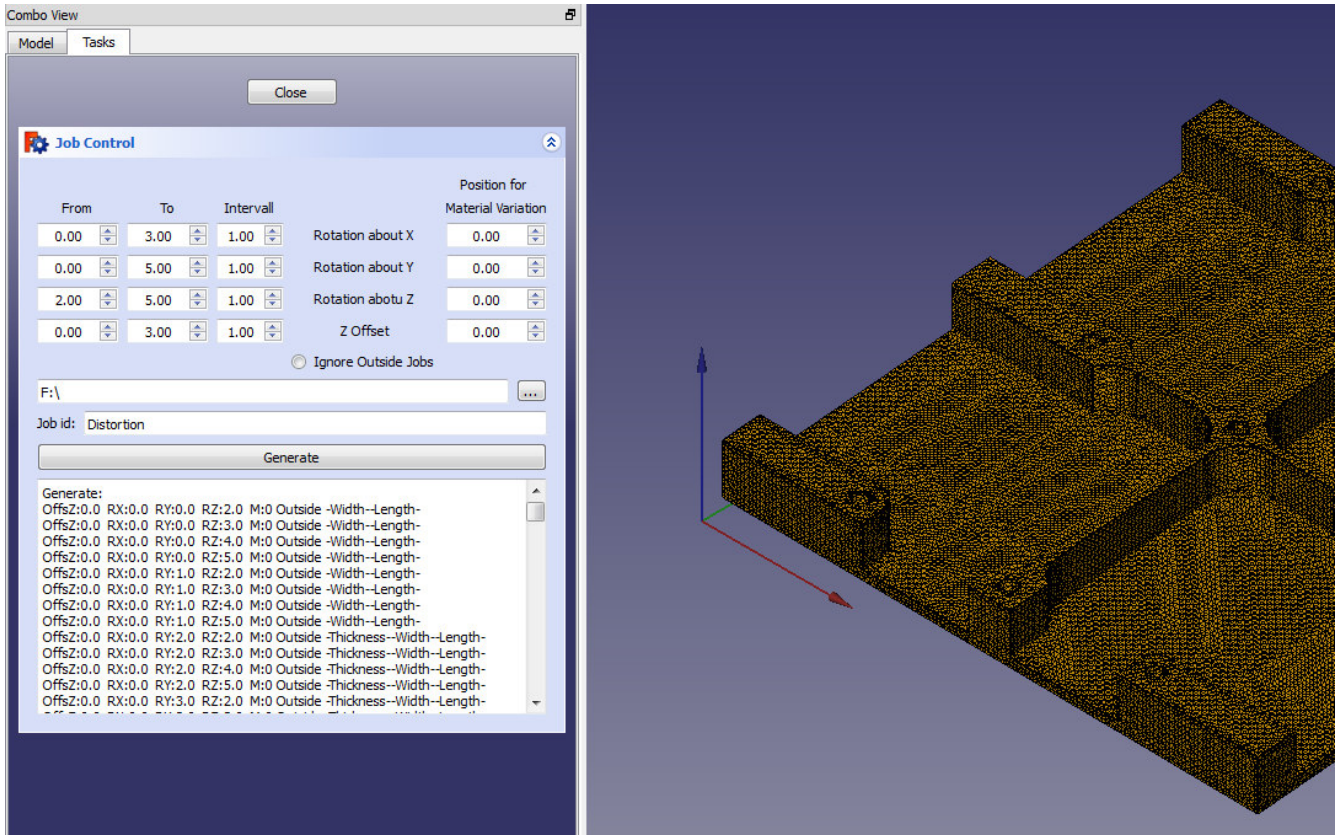


Figure 69: Generate Jobs menu at FreeCAD.

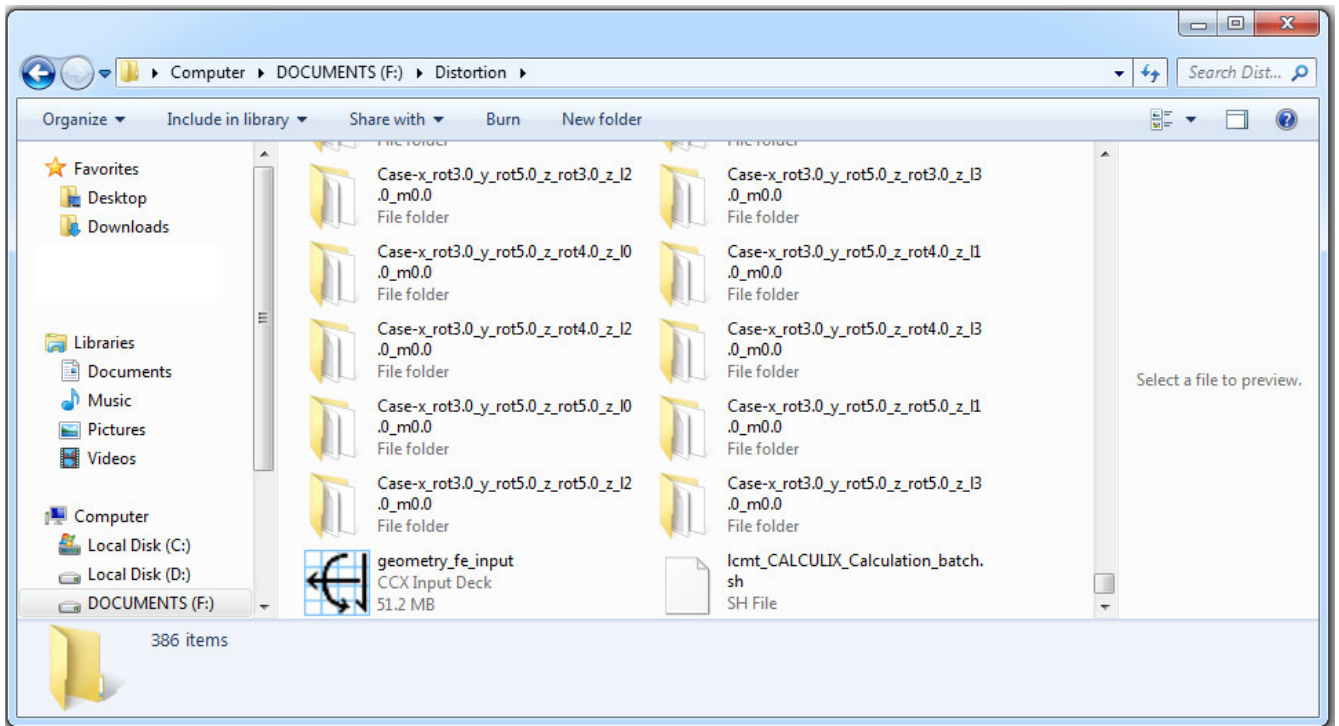


Figure 70: Files generated for each position required in analysis.

CalculiX Processing

Once the positions for the analysis have been defined, the simulation process is performed, CalculiX solver is used for this propose. A general input file was generated at the final stage of pre-processing, containing all the information for the simulation, extra input file is added for each position specifying the conditions for the specific simulation, stress profiles, plate thickness and position into the plate.

The simulation needs initial conditions for isostatic simulation, this initial state is the residual stress values for each node before the static analysis, these stress values are mapped from the functions for each direction, L rolling direction (σ_x) and LT transversal direction (σ_y). This mapping process is performed for each positioning case, CalculiX reads the files for each simulation and interprets the position of the part mapping the stresses into each node. The fitting functions are of the form $\sigma(z)$ where a stress value is calculated when specifying the z position into the plate thickness for each node.

SIGINI Fortran Script for Stress Mapping

The stress mapping process is performed by a Fortran script, the SIGINI user-subroutine script define initial stress fields at particular material points, it is called at the start of the analysis for each applicable material calculation point in the model, and can be used to define all active initial stress components at material points as functions of coordinates, element number, integration point number, etc. The number of stresses components that must be defined depends on the element type for which this call is being made. The order in which the components must be defined is the same as in the element definition. For example, in three-dimensional continuum elements six stress components must be defined in the order $\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{12}, \sigma_{13}, \sigma_{23}$ for each integration point. The developed script defines σ_{11} and σ_{22} only, L and LT direction residual stresses.

Variables to be defined are **SIGMA(1)** [First stress component], **SIGMA(2)** [Second stress component], **SIGMA(3)**, etc.

Variables passed in for information are **COORDS** [An array containing the initial coordinates of this point], **NTENS** [Number of stresses to be defined, which depends on the element type], **NCRDS** [Number of coordinates], **NOEL** [Element number], **NPT** [Integration point number in the element], **LAYER** [Layer number (for composite shells and layered solids)], **KSPT** [Section point number within the current layer], **LREBAR** [Rebar flag. If LREBAR=1, the current integration point is associated with element rebar, otherwise, LREBAR=0], **NAMES(1)** [Name of the rebar to which the current integration point belongs, which is the name given in the rebar or rebar layer definition. If no name was given in the rebar or rebar layer definition, this value will be blank. This variable is relevant only when LREBAR=1] and **NAMES(2)** [Element type name].

The developed SIGINI script reads COORDS, NTENS, NCRDS variables and gives SIGMA(1) and SIGMA(2) for each node depending the position in z (plate thickness), evaluating the fitted residual stress functions. The general form of SIGINI script is shown below, Appendix D shows the script used for stress mapping before simulation.

SIGINI subroutine interface is the next:

```
SUBROUTINE SIGINI(SIGMA,COORDS,NTENS,NCRDS,NOEL,NPT,LAYER,  
1 KSPT,LREBAR,NAMES)  
C  
INCLUDE 'ABA_PARAM.INC'  
C  
DIMENSION SIGMA(NTENS),COORDS(NCRDS)  
CHARACTER NAMES(2)*80  
  
user coding to define SIGMA(NTENS)  
  
RETURN  
END
```

Simulation

Into the analysis folder "Distortion" is located a batch .sh file, containing the instructions to run each case simulation, a Fortran compiler is needed for SIGINI run in each analysis, GFortran-GCC free compiler is available for Linux environment, it is strongly recommended to work in Linux operative system during all the process (FreeCAD is available in Linux). Figure 71 shows a terminal placed into the folder where the batch .sh file is located, the instruction to run the batch file must be introduced into the terminal (./lcmt_CALCULIX_Calculation_batch.sh).

After this instruction, the CalculiX executable file will run solving for each simulation case. Figure 72 shows the execution of CalculiX.

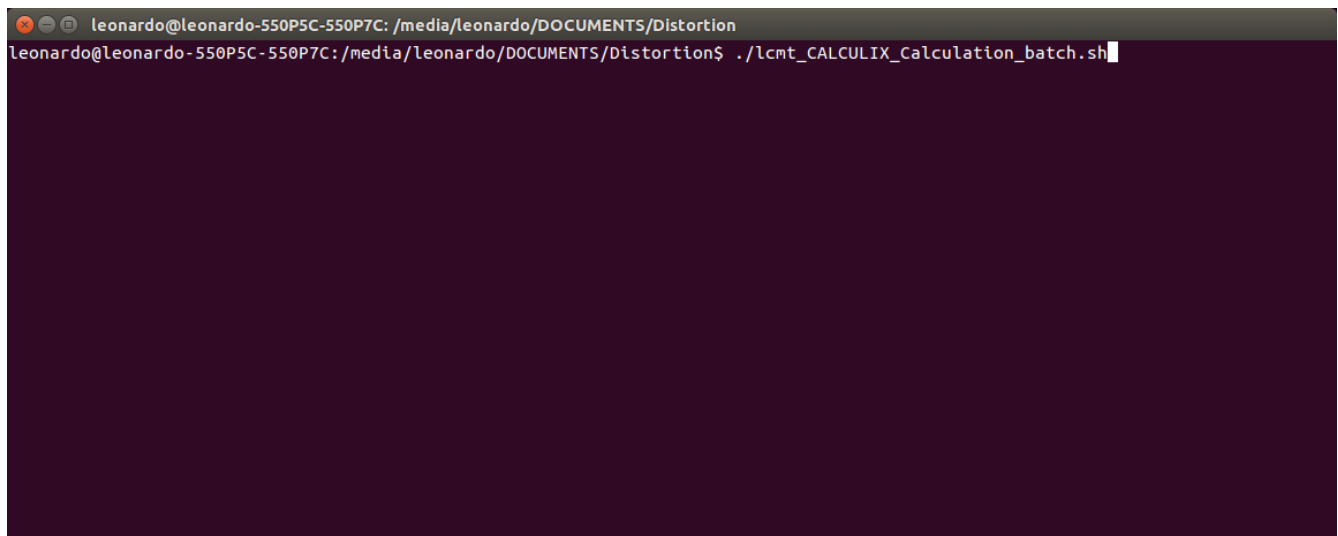


Figure 71: Batch file open in a linux terminal.

```
leonardo@leonardo-550P5C-550P7C:/media/leonardo/DOCUMENTS/Distortion$ ./lcm_CALCULIX_Calculation_batch.sh
*****
CalculiX Version 2.10, Copyright(C) 1998-2015 Guido Dhondt
CalculiX comes with ABSOLUTELY NO WARRANTY. This is free
software, and you are welcome to redistribute it under
certain conditions, see gpl.htm
*****
You are using an executable made on mié may  4 08:43:57 CDT 2016

The numbers below are estimated upper bounds
number of:

nodes:          684895
elements:       428746
one-dimensional elements:      0
two-dimensional elements:      0
integration points per element: 4
degrees of freedom per node:   3
layers per element:            1

distributed facial loads:       0
distributed volumetric loads:  0
concentrated loads:            0
single point constraints:       6
multiple point constraints:     7
terms in all multiple point constraints: 25
tie constraints:                0
dependent nodes tied by cyclic constraints: 0
dependent nodes in pre-tension constraints: 0

sets:           3
terms in all sets: 1798533
```

Figure 72: Execution of CalculiX for each simulation.

Once the calculation has finished, into each folder there will be five extra files. Figure 73 shows the files generated after CalculiX analysis.

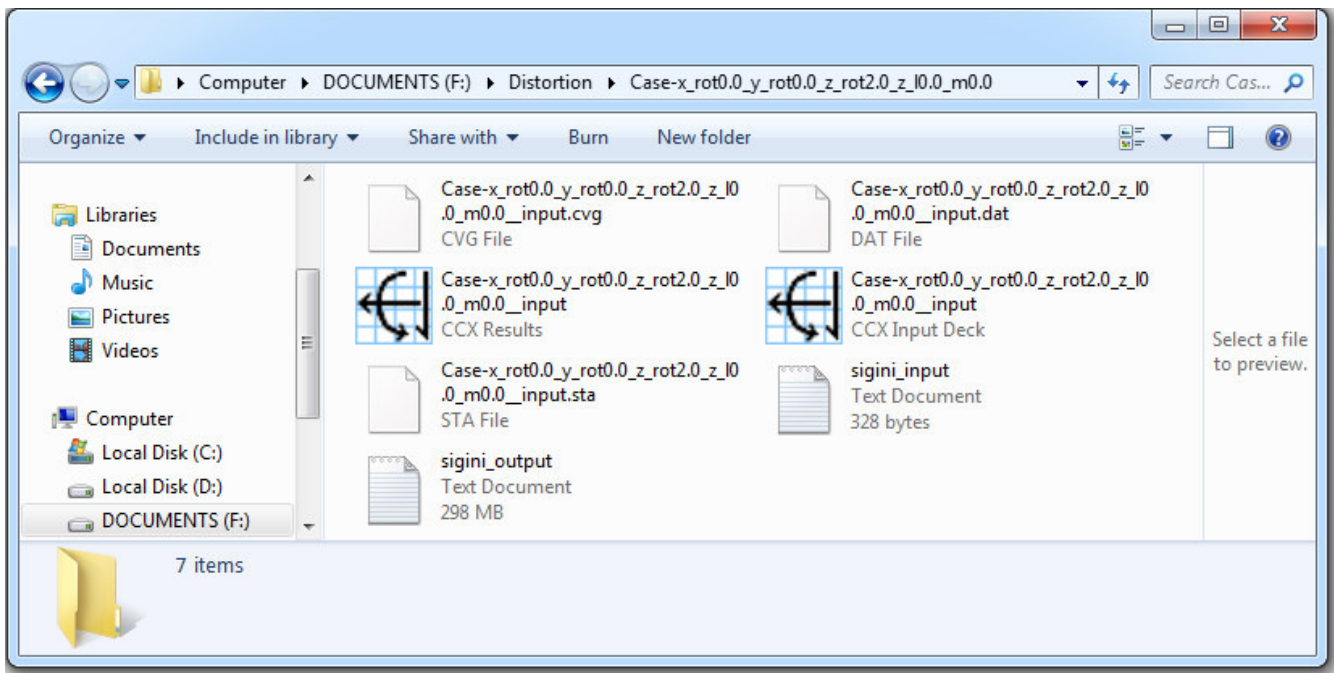


Figure 73: Execution of CalculiX for each simulation.

The file .frd is a CCX Results document containing the output of the simulation (stresses and deformations) it can be opened by CalculiX GraphiX (cgx), Figure 74 shows the cgx interface, showing the distortion in Z direction results (D3) from a specific position of the case study, in this case 10.5 mm Z offset (top of the plate).

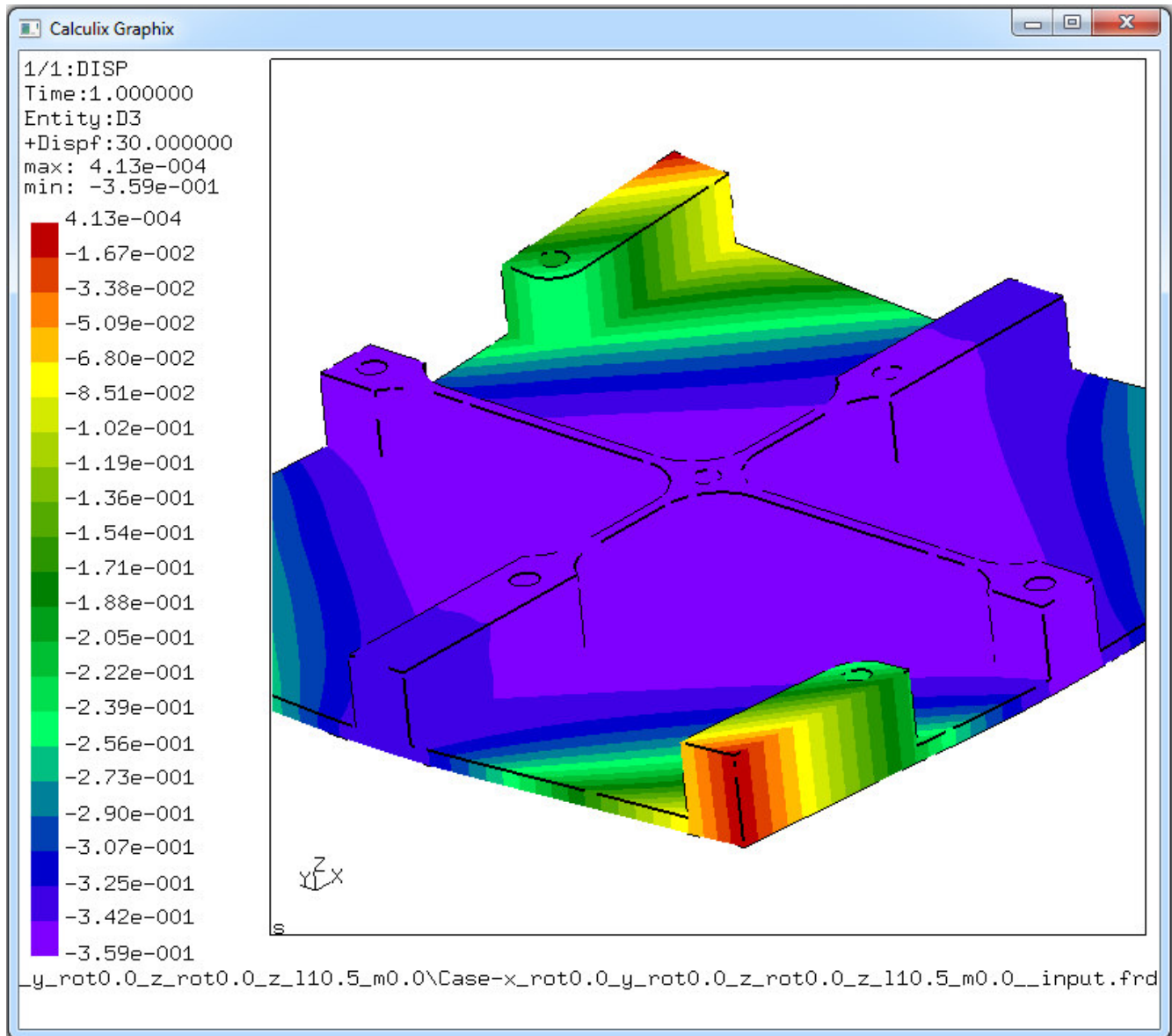


Figure 74: CalculiX GraphiX interface for results visualization. Distortion in Z direction (D3) for 10.5 mm Z offset.

R Statistical Post-Processing

After having the results of the simulation, **Read results** module in FreeCAD synthesizes the results in an .csv format file creating a list of the cases of the analysis and the minimal and maximal values of distortion in X, Y and Z directions. When selecting the module, a navigation window will appear to specify the location of the result files, then it will read each result file and create two .csv files in this location, one for the positioning analysis and the other for coefficients of residual stress function variation if available. Appendix F shows the .csv tables generated from the lecture of the Case Study, for position (from 0 to 10.5 mm Z Offset every 1.05 mm) and for material variation ($\pm 10\%$ variation for the 6 coefficients of L direction and $\pm 10\%$ variation for the coefficients of LT direction.)

Fractional Factorial Design

The material properties depends on several aspects and variables, sometimes difficult to control, starting with micro-structure of the materials, metals are polycrystalline materials, meaning that it contains multiple structural cells randomly oriented, then the manufacturing processes for plate (casting, homogenization, hot rolling, solution heat treatment, quenching, stretching and aging) modifies the micro-structure of the material and generate residual stress values. The primary processes that affect residual stress are stretching and quenching. During the stretching process the stretching distance and plastic variation are considerable variables. For quenching process, the plate thickness and water pressure/flow ratio, are the two main factors. The residual stress profiles are not always the same for different plates subjected to the same processes; all variables involved during each process modifies the residual stress values in a percentage range. Figure 75 shows the residual stress profile of a plate, then it is rounded by an envelop representing the residual stress variation due these factors.

The residual stress profiles depends also on the location of the portion of the mother plate that will be machined, the homogeneous quality is better at the central portion of the mother plate. Theoretically, the stress profiles are the same in all extensions of the plate and the proposed workflow assumes this considerations, nevertheless the stretching process makes inhomogeneous the edges of the mother plate. The plates are manufactured by lots and any lot has exactly the same characteristics. A way to represent this material residual stress variation due uncontrollable factors is when residual stresses coefficients defined in equation 1 are changed at some specific percentage value, when defining 90% of the coefficients, the residual stress fitted curve will decrease the stresses values without changing the shape of the curve. To measure the robustness of the solution found on simulation, a 2 levels fractional factorial design is performed in order to analyze main effects and interaction effects.

As the number of factors in a 2^k factorial design increases, the number of runs needed for a full analysis increases exponentially. From the total number of runs, only a small fraction of the cases correspond to main effects, and few cases correspond to two-factors interactions, most of the cases corresponds to three factor or higher interactions. To reproduce the material variation due previously mentioned factors, 2 levels fractional factorial design with independent coefficient variation can be designed from the FreeCAD **Part Distortion** module in **Material fit** section. Appendix C contains all the 2 levels fractional factorial designs depending on the number of coefficients that have variation.

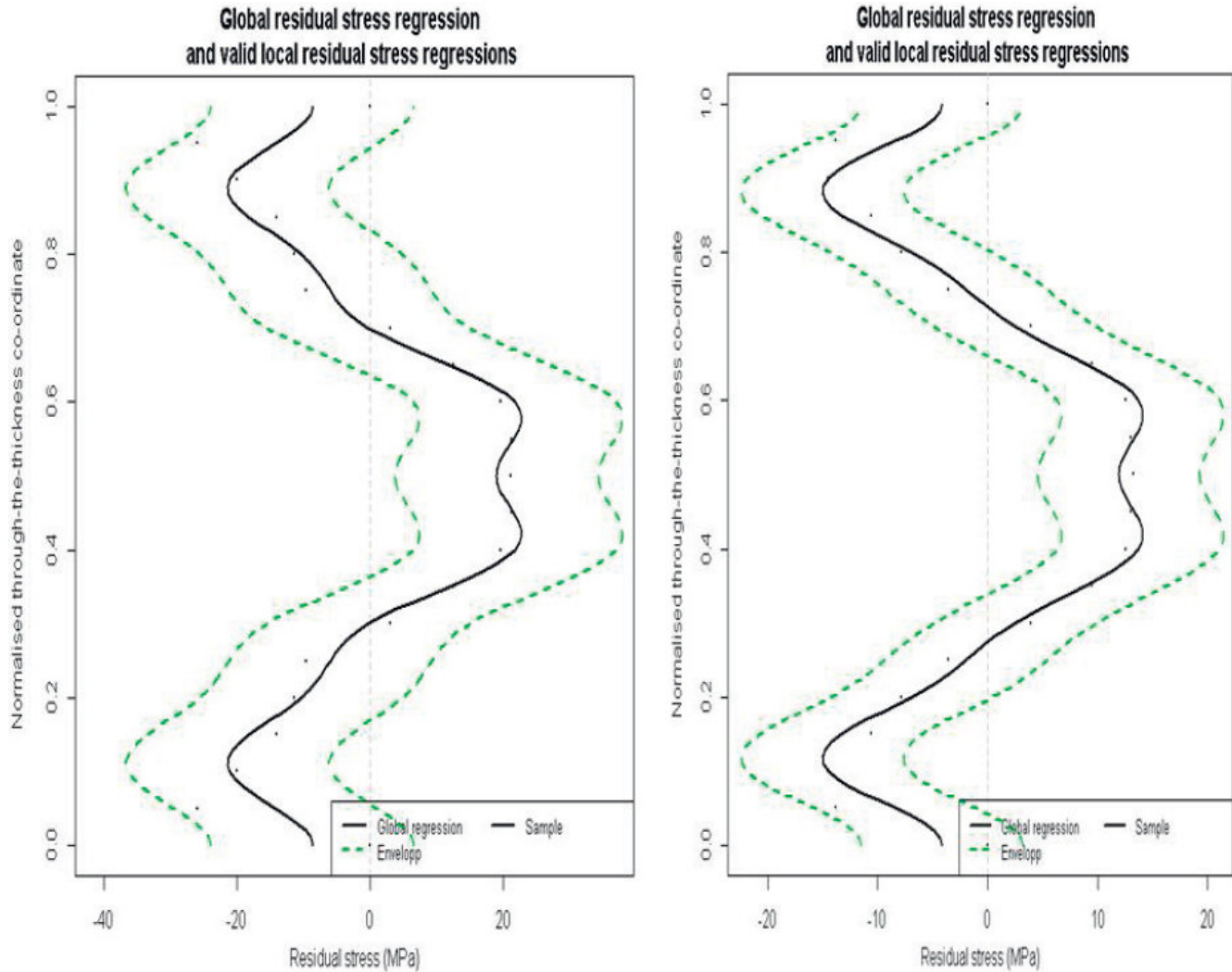


Figure 75: Residual stress profiles range and variability due material and processes variables. a) Longitudinal direction, b) Long transverse direction. [11]

Results Report

Once the .cvs files have been generated from files results reading on FreeCAD **Read Results** section, an R code can be generated for visual results report (plots of results). FreeCAD **Report Results** section can generate specific report depending on user requirements, Figure 76 shows the **Report Results** section interface, where 2 different reports can be generated, one for material positioning and general material variation and the other for the 2 level fractional factorial design of material variation, configuration for case study is chosen in this section. The variables of interest can be chosen going from 1 variable plotted against a result, this result can be also specified if distortion in an specific direction is analyzed. If more than 1 variable is chosen, 3D combinational plots will be run, generation a surface with 2 variables combinations against the chosen result.

For 2 levels fractional factorial design, only a response can be chosen, the analysis will take into account influence of coefficients variation for the specified response.

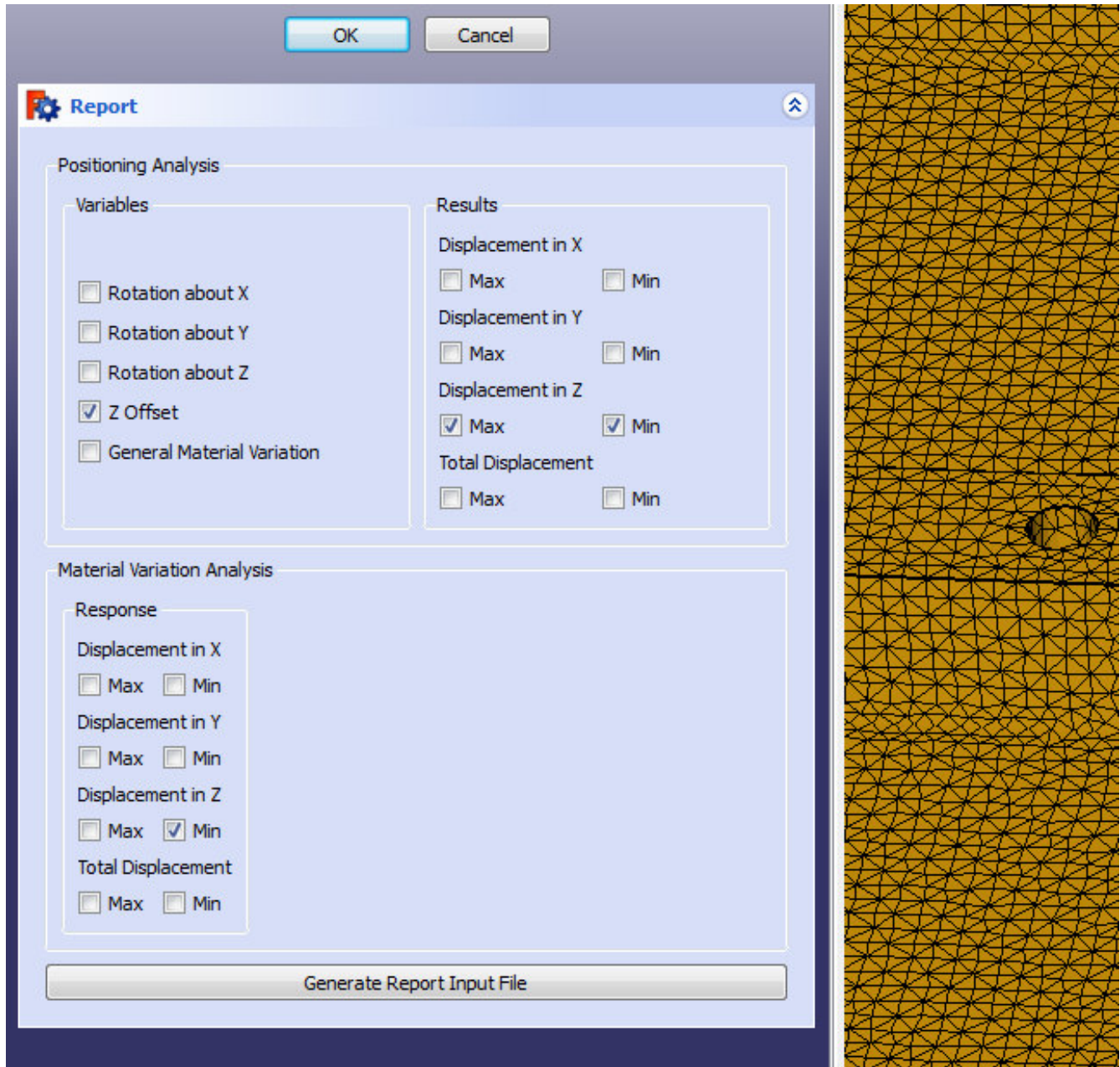


Figure 76: Report Results section interface, results option for case study are checked

An report input file will be generated ready to be run by R software, this input file will contains the user specifications for a .pdf file containing the plots of interest. For the case study, only Z Offset variable had variation, distortion in Z direction (positive and negative deflection) is analyzed, from the .cvs file, displacement in Z maximal and minimal values for each simulation represents maximal deflection. Appendix G shows the outcome after running the generated R code for positioning analysis (Z offset against maximal and minimal displacement in Z) and the previously mentioned 2 levels fractional factorial design for material variation. ($\pm 10\%$ variation for the 6 coefficients of L direction and $\pm 10\%$ variation for the coefficients of LT direction).

VI Machining Test & Validation

From the case study, two positions are chosen for the validation of the methodology, one for high distortion and the other for an optimal position, the simulations was run for 10 positions [0, 1.05, 2.1, 3.15, 4.2, 5.25, 6.3, 7.35, 8.4, 9.45 & 10.5] mm in z offset (translation through z axis). The easiest positions to be machined are for 0 mm and 10.5 mm Z offset, both have high distortion values. The 10.5 mm z offset is chosen for first part. The optimal position is in 3.15 mm Z offset, both parts where measured with a 3D high accuracy scan; results are compared with predicted distortion from simulations and discussed.

CNC Characteristics & Machining Variables Analysis

The University of Guanajuato has a VMC 3016 CNC machining center at campus. The information taken from [22] shows the basic characteristics and properties of this CNC machining center. Figure 77 shows the general dimensions of the machining center; Figure 78 shows the characteristics and specifications; Figure 79 shows the machining table dimensions and Figure 80 shows the slot dimensions into the machining table.

The machining variables described in chapter I have and important effect into the general distortion results; generally the machining process induce some stress to the workpiece, the machining variables can increase or decrease these induced stresses during the process.

The objective when machining is to avoid or induce as less stresses as possible during the process, from literature some values are analyzed for machining with low stress generation. Drilling and milling are performed for the total manufacturing process of the case study, Table 12 shows these variables for the process performed for the machining of the proposed part.

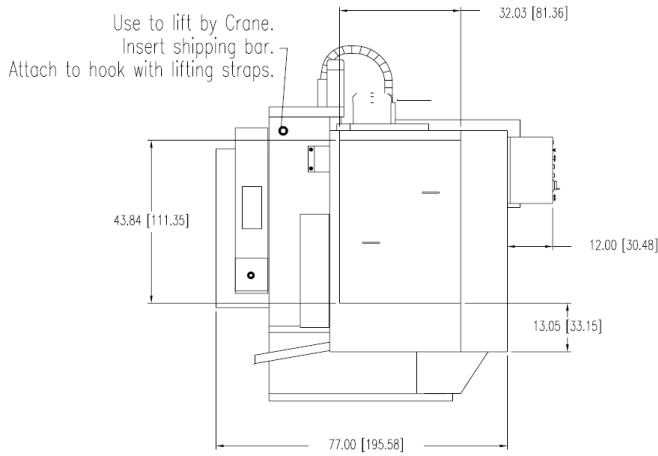
Variables	Process	
	Drilling	Milling
Tool diameter (D)	0.5 in	2 & 4 in
Feed rate (v)	1 in/min	2 in/min
Depth by path (d)	-	0.04 in

Table 12: CNC machining variables values used for manufacturing of the case study part

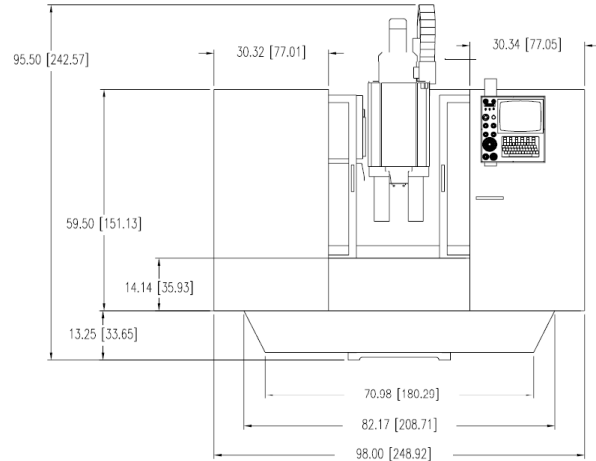
Fadal

Maintenance Manual

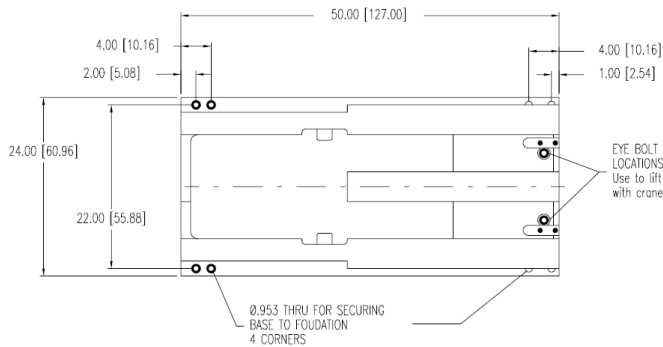
VMC 3016



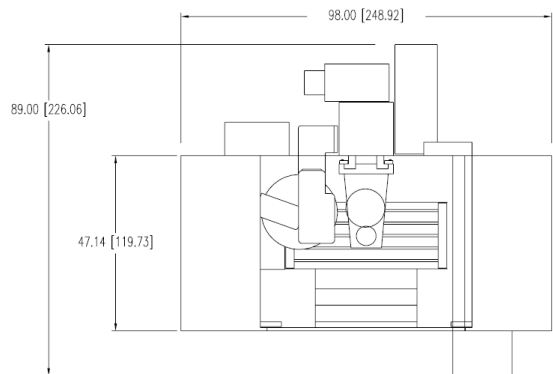
SIDE VIEW



FRONT VIEW



**TOP VIEW
BASE
SCALE 2:1**



TOP VIEW

Figure 1-5 VMC 3016

Note: Dimensions represented in inches & [centimeters]

Table 3: VMC 3016 Specifications

3016 Specifications	3016 Standard	3016 Metric
Table Size	39" x 16"	750mm x 406mm
Floor to Table	31"	787mm
T-Slots (No. x Width x Span)	3 x .562" x 4.33"	3 x 14mm x 110mm
Cutting Feed Rate	.01-400 ipm (600 @ 150%)	.25-10,160 (15,240 at 150%)mm/min.
Rapid Feed Rate (X/Y/Z)	900 ipm (X/Y) 700 ipm (Z)	22.8 m/min. (X,Y) 17.7 m/min (Z)
Max. Weight on Table	2,736 lbs.	1,241 kg.
Axis Drive Motor (X/Y/Z)	AC, 3,800 lbs peak thrust	AC, 16.900 N* thrust
Ball Screw Size	40mm Dia. (X/Y/Z)	
Longitudinal (X Axis)	30"	762mm
Cross (Y Axis)	16"	406mm
Vertical (Z Axis)	20" (28" Opt.)	508mm (711mm Opt.)
Spindle Nose to Table	4"-24" (4"-32" Opt.)	102mm-610mm (102mm-813mm)
Spindle Center to Column Ways	16"	406mm
Main Motor - Automatic 2 Speed Vector	15 HP*, 11.2 KW	
Opt. HT Motor - Automatic 2 Speed Vector	22.5 HP*, 16.8 KW	
Torque	160 ft-lbs, 220 ft-lbs (HT)	220 Nm/300 Nm
Accuracy, Axis Positioning	± .0002"	.0050mm
Accuracy, Axis Repeatability	± .0001"	.0025mm
Glass Scales (X/Y/Z)	Optional	
Spindle Speed	10-10,000 rpm (15,000 Opt.)	
Spindle Orientation	Electromechanical	
Spindle Taper	No. 40	
ATC, Number of Tools	21	
ATC, Tool Selection	Random, Bi-directional	
Max. Tool Diameter	3" (4.5" w/o adjacent tools)	76mm (114mm w/o adjacent tools)
Max. Tool Length	15"	381mm
Max. Tool Weight	15 lbs.	6.8 kg
Machine Width and Depth	98" W x 77" D	2.5m W x 2m D
Machine Maximum Height	103"	2.6m
Machine Weight	8,550 lbs.	3,878 kg
Air Pressure Reqs. (Momentary)	120 psi, 15 scfm	5.5 Bar
Power Reqs. (3-phase)	40/45 amps, 230 VAC (20/25 480 VAC)	
Single Phase (Optional)	60 amps, 230 VAC	
Cool Power System	Spindle, Headstock, Ballscrews	
Ball Screw Supports (X/Y/Z)	dual	
No. of Ground Boxways per Axis (X/Y/Z)	2	

* Rated Peak Value

Figure 78: General characteristics and specifications of VMC 3016 CNC machining center. [22]

2216 & 3016 Table

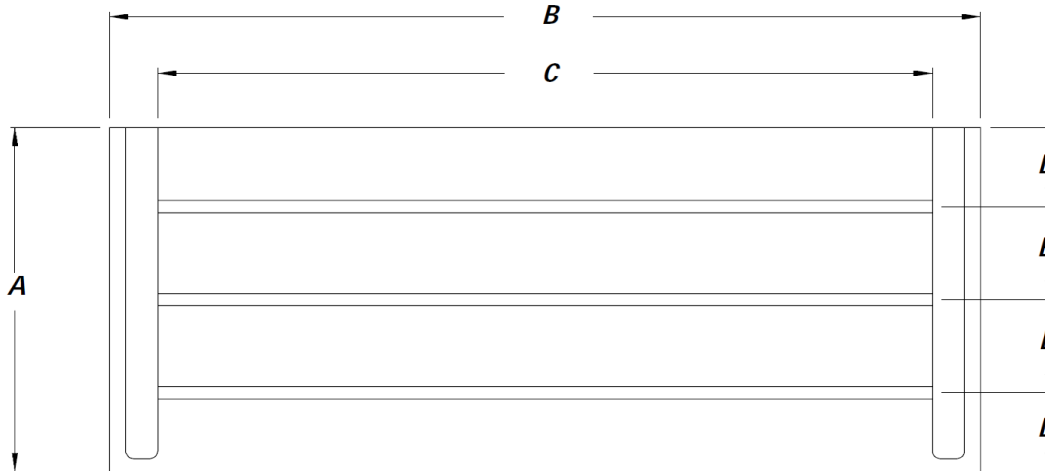


Figure 1-18 2216 & 3016 Table

A = 16.00" (40.64mm) B = 40.50" (1028.7mm) C = 36.00" (914.4mm)
 D = 3.67" (93.22mm) E = 4.33" (109.98mm)

Figure 79: Machining table dimensions of VMC 3016 CNC machining center. [22]

**EMC, 15, 15XT,
2216, 3016, 2016L
& 3016L T-Slots**

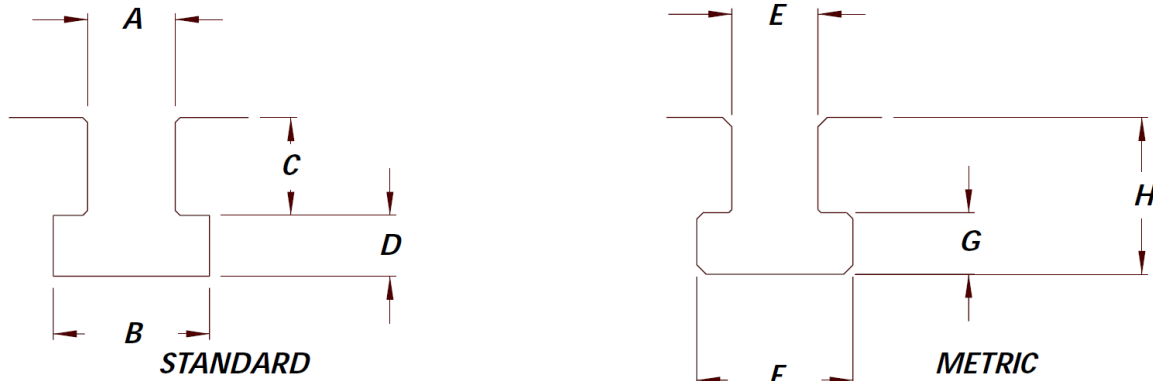


Figure 1-20 EMC, 15, 15XT, 2216, 3016, 2016L & 3016 T-Slots

Standard T-Slot Dimensions:

A = .5625"-.5645" (14.26-14.34mm) B = .970" (24.64mm)
 C = .625" (15.88mm) D = .390" (9.91mm)

Metric T-Slot Dimensions:

E = .5510-.5525" (14-14.03mm) F = .915-.975" (23.29-24.765mm)
 G = .364-.424" (9.25-10.77mm) H = 1.004" (25.5mm)

Figure 80: Slot dimensions into the machining table dimensions of VMC 3016 CNC machining center. [22]

Machining Steps & Setup for Selected Positions

Two plates (Al 7050-T7451) were donated by Kaiser Aluminum industry for research proposes in this project, one with high residual stress profiles and the other with low residual stress profiles. The first analyzed plate is the low residual stress profile plate (B Plate).

Figure 81 shows the dimensions of the plate provided by Kaiser and the sectioning for machining (maximal dimensions for machining at the 3016 CNC center at campus is 15.8" x 15.8"). The plates are sectioned by sawing cutting process, Figure 82 shows the process.

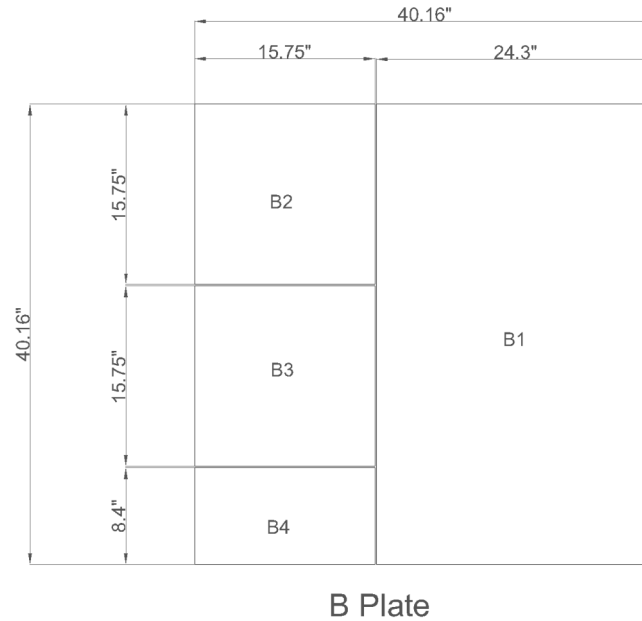


Figure 81: Sectioning of the Al 7050-T7451, 2" thick plate provided by Kaiser.



Figure 82: Sawing cutting process for sectioning of the plates.

Manufacturing Process for 10.5 mm Z Offset Position of the Case Study

The first manufactured part was positioned 10.5 mm from lower surface, this is the easiest position to machine, the part is the B2 section from the mother plate.

Step 1- Drilling

The first step is the drilling for further fixing when machining, following the next sequence:

- Nuts were introduced into the machining table slots for further fixing.
- The plate was fixed sideways left and right for drilling. Orientation is crucial as the part is asymmetrical; according to simulations, rolling direction is vertical in the planar machining table.
- The center point of the plate was marked and defined as coordinates origin.
- The other eight points were marked referred from the center point as seen in Figure 83.
- The drilling process was performed for total plate thickness (2 in) with a 0.5 in diameter shank at 350 rpm and 1 in/min feed rate.

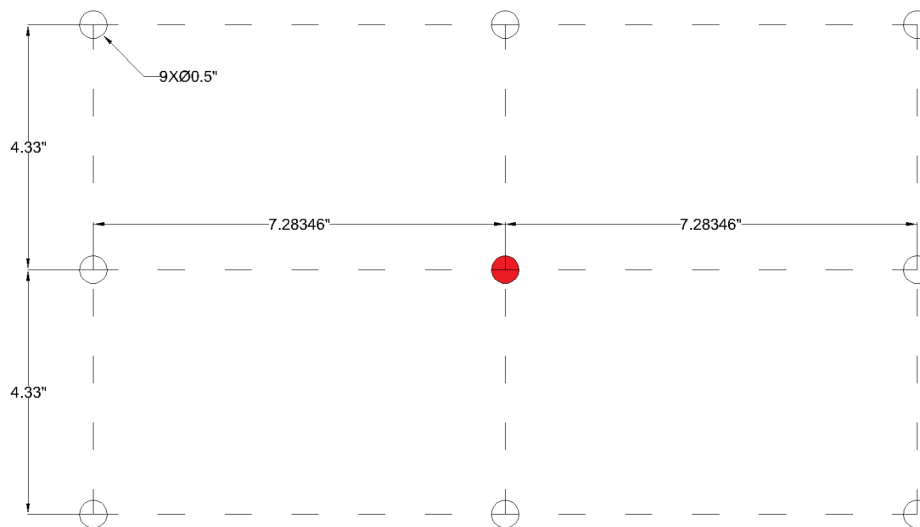


Figure 83: Schema of drilling points for fixing referred to center point.

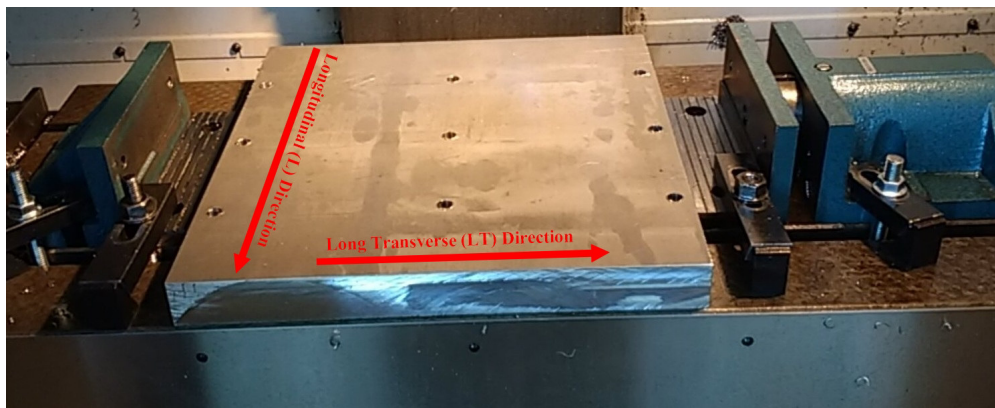


Figure 84: B2 Plate after drilling process.

Step 2- Fixing Boxes

The second step is the milling for fixing boxes. Still fixed sideways, the boxes described in Figure 85 and Figure 86 are machined in order to let further fixing when high portion of material is removed. The mill is 2 in diameter, at 91 rpm, 2 in/min feed rate and 0.04 in deep by path, machining a total deep of 0.41" (10.5 mm). Bolts are used for machined boxes when possible to ensure fixing.

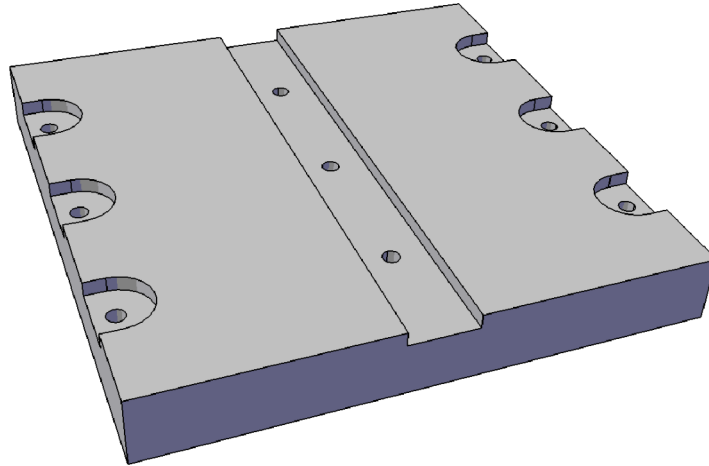


Figure 85: 3D solid model of the plate after machining of fixing boxes.

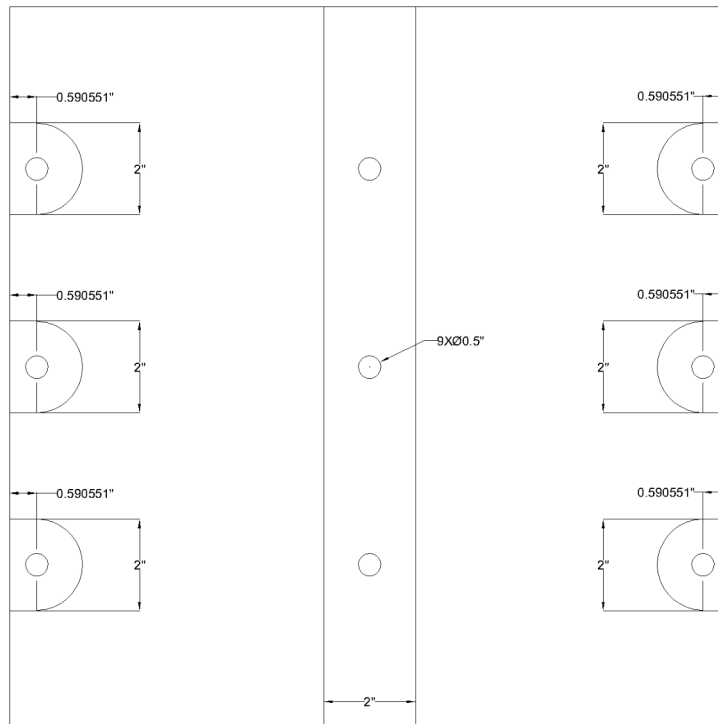


Figure 86: Schema of 0.41" deep boxes for further fixing.



Figure 87: B2 plate during milling process for fixing boxes.



Figure 88: B2 plate after milling process for fixing boxes.

Step 3- Flattening Lower Surface of the Part

As the part is positioned 10.5 mm from the lower surface of the plate, after fixing boxes machining, the removal of the rest of the material is performed. After flattening, this surface will be the lower surface of the part. The first stage is to fully fix the part with 9 bolts as seen in Figure 89.

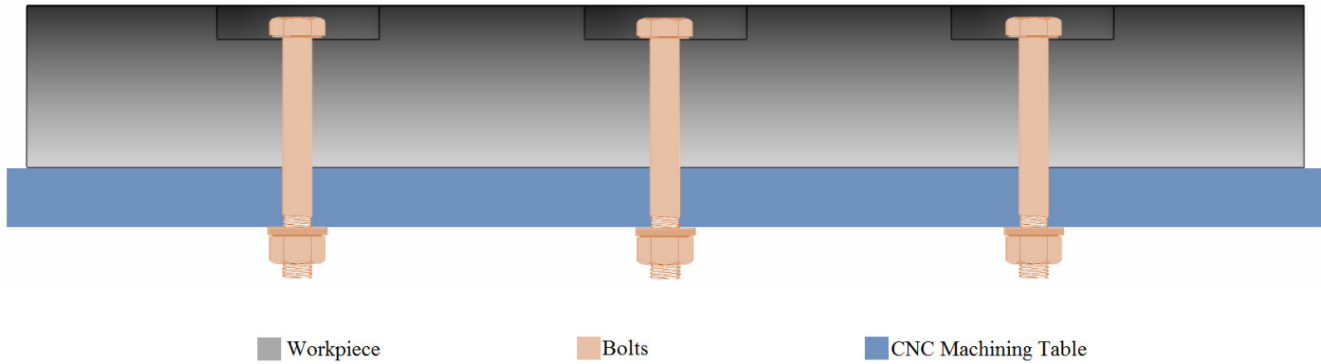


Figure 89: 2D Schematic. Fully fixing of the part before flattening machining.



Figure 90: Fully fixed B2 plate ready for flattening process.

Once fixed, the 10.5 mm material layer is removed to have the lower surface of the part totally flatted. Figure 91 shows the removal of the 10.5 mm material layer (flating process). The mill is 4" diameter, at 91 rpm, 2 in/min feed rate and 0.04" deep by path, machining a total deep of 0.41" (10.5 mm).

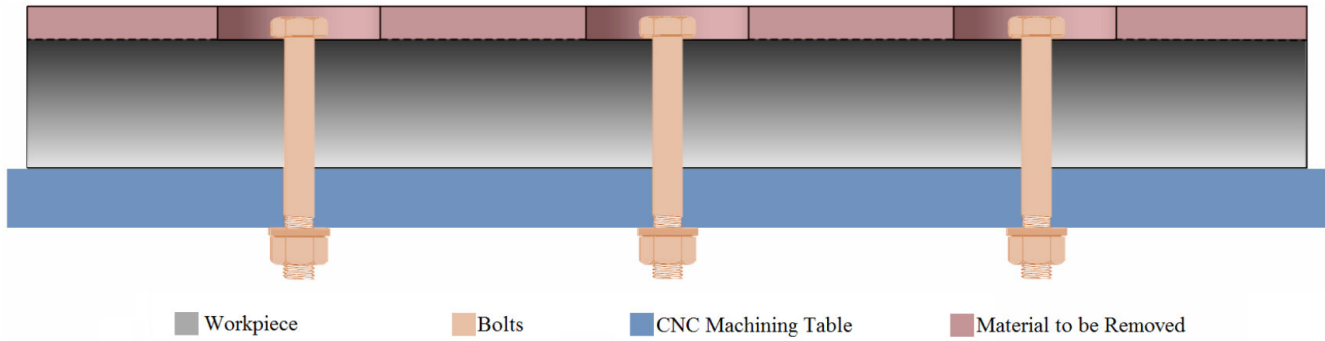


Figure 91: 2D Schema. Removal of the 10.5 mm material layer for flating.



Figure 92: B2 part after flating process.

Step 4- Machining of the part

Once the lower surface of the part has been flatted, the plate is released and flipped in order to have the recently flatted surface in contact with the machining table.

The part is fixed again ensuring that the lower surface is totally flat in contact with the machining table (some distortion is expected from the 10.5 mm layer removal).

Figure 93 shows an schema of the fixed part once it has been flipped. Once fixed, the part is machined to obtain final geometry, a 4" diameter mill is used, at 91 rpm, 2 in/min feed rate and 0.04" deep by path. Figure 94 shows the schema of the final machining process.

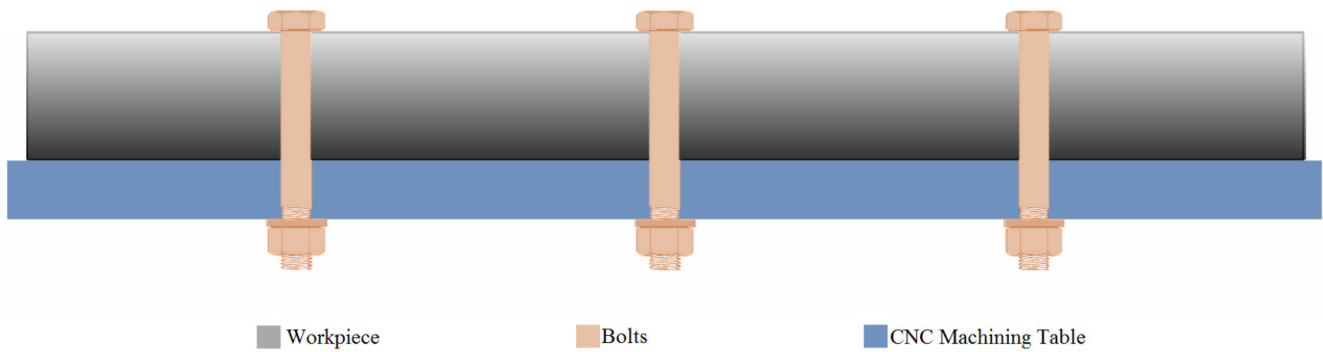


Figure 93: 2D Schema. Fully fixing of the flipped part after flattening.

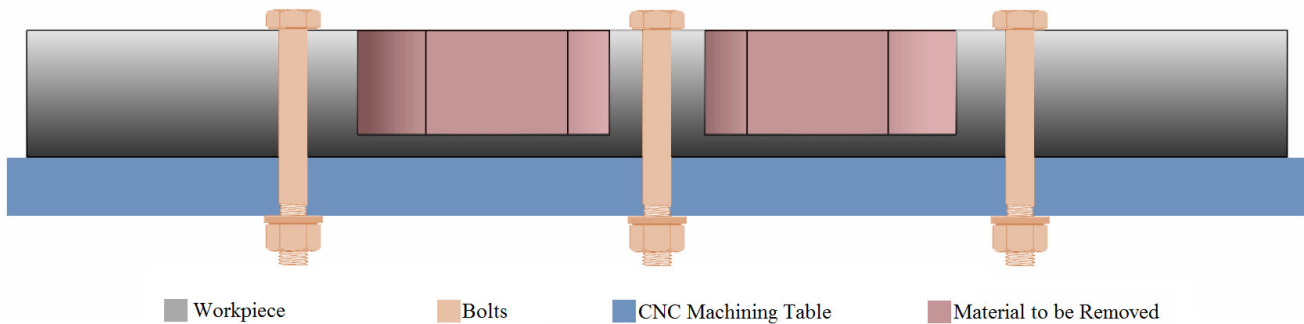


Figure 94: 2D Schema. Final machining process for proposed geometry.

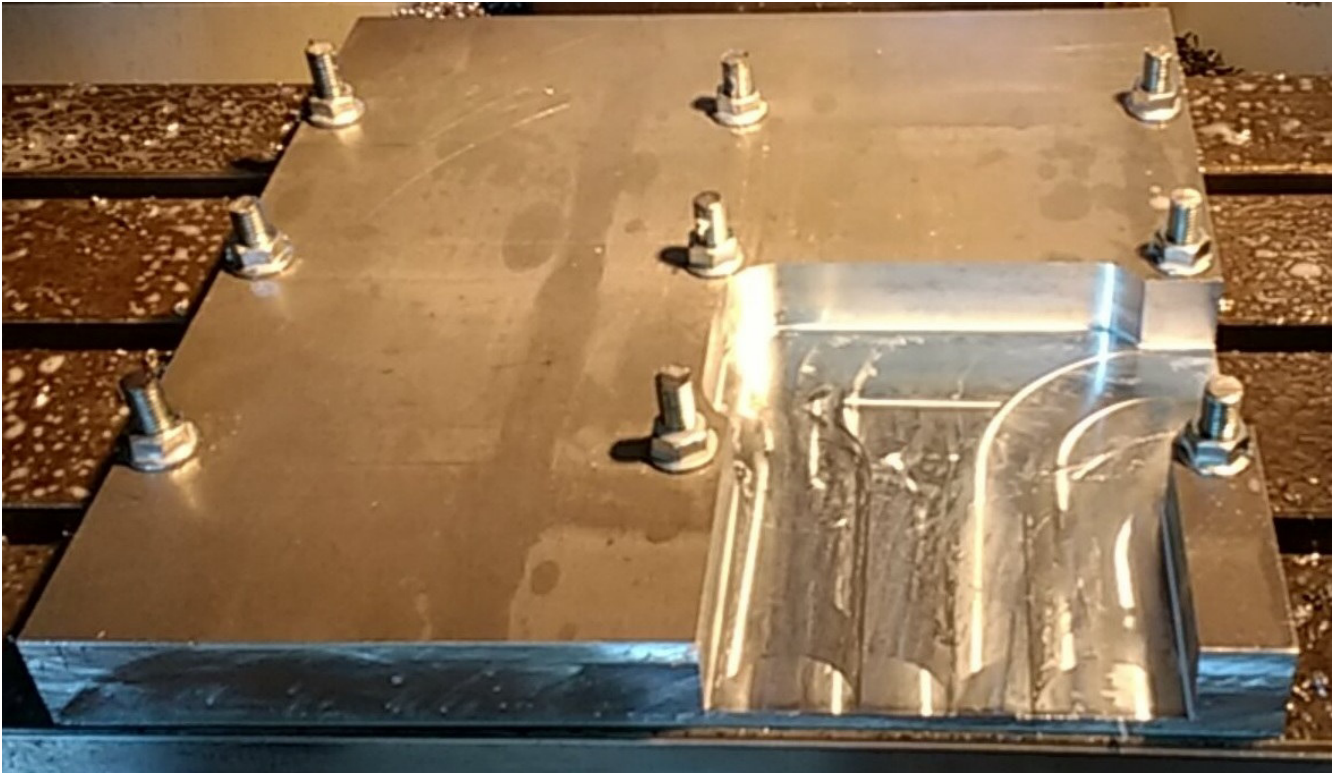


Figure 95: B2 part after 4th quadrant machined.

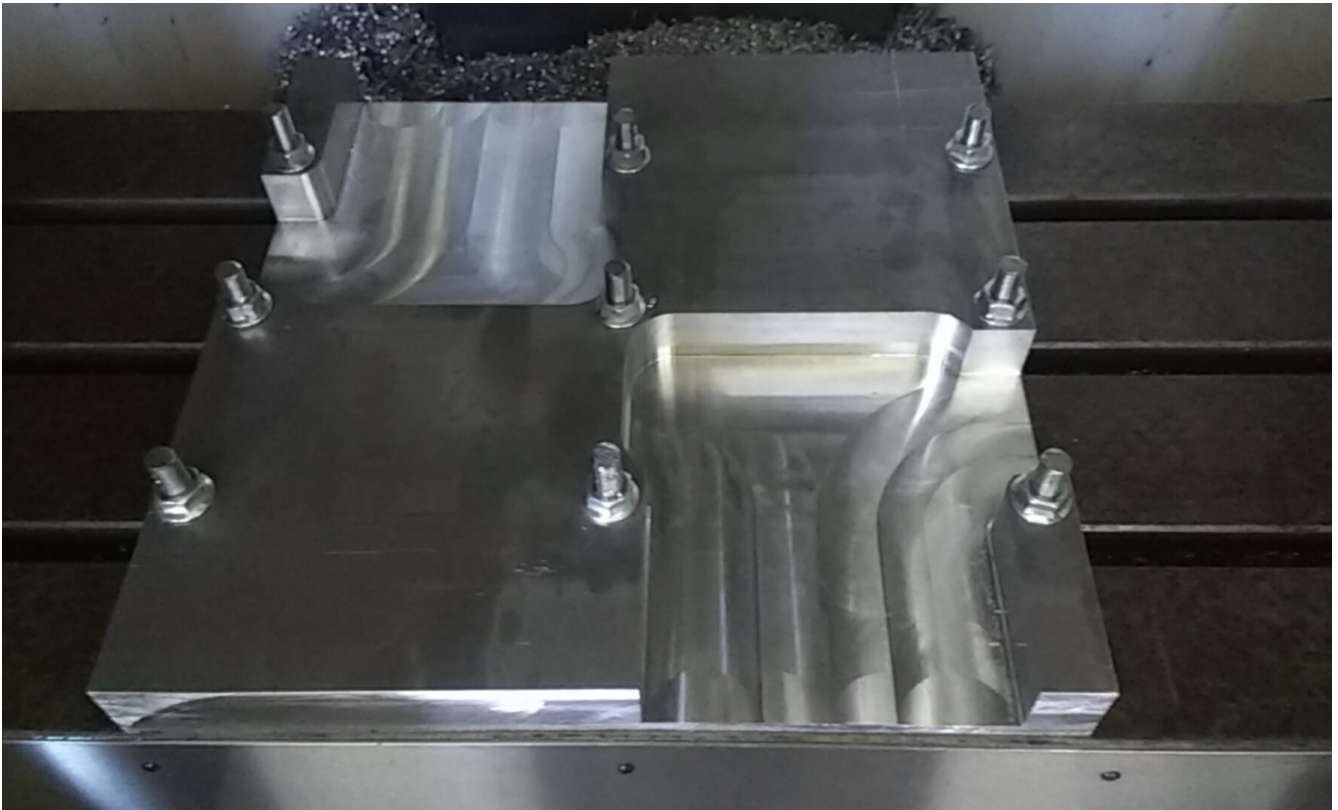


Figure 96: B2 part after 2nd quadrant machined.



Figure 97: B2 part after machining before released, case study geometry.

Manufacturing Process for 3.15 mm Z Offset Position of the Case Study

The second manufactured part was positioned 3.15 mm from lower surface, this is the easiest position to machine, the part is the B3 section from the mother plate.

Step 1- Drilling

The first step is the drilling for further fixing when machining, following the next sequence:

- Nuts were introduced into the machining table slots for further fixing.
- The plate was fixed sideways left and right for drilling. Orientation is crucial as the part is asymmetrical; according to simulations, rolling direction is vertical in the planar machining table.
- The center point of the plate was marked and defined as coordinates origin.
- The other eight points were marked referred from the center point as seen in Figure 98.
- The drilling process was performed for total plate thickness (2 in) with a 0.5 in diameter shank at 350 rpm and 1 in/min feed rate.

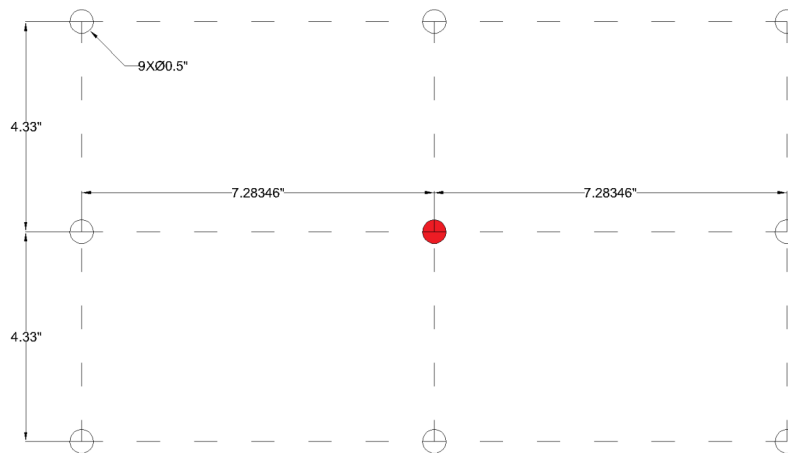


Figure 98: Schema of drilling points for fixing referred to center point.

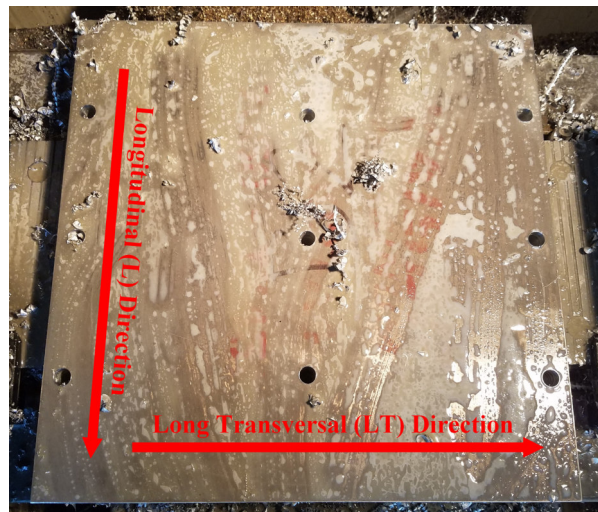


Figure 99: B3 plate after drilling process.

Step 2- Fixing Boxes

The second step is the milling for fixing boxes. Still fixed sideways, the boxes described in Figure 100 and Figure 101 are machined in order to let further fixing when high portion of material is removed. The mill is 2 in diameter, at 91 rpm, 2 in/min feed rate and 0.04 in deep by path, for this case, boxes in both sides are needed, one with 0.124" deep (3.15 mm z offset, optimal position) and the other with 0.289" (7.35 mm deep, rest of the material). Bolts are used for machined boxes when possible to ensure fixing. First Boxes are the 0.289" deep, then the B3 plate is flipped to machine the 0.124" boxes.

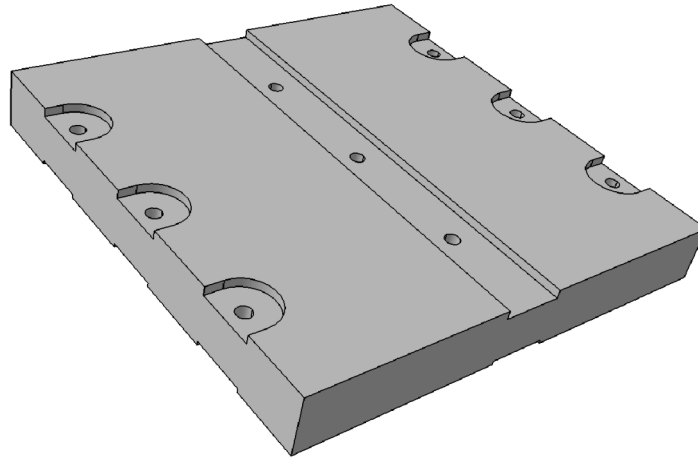


Figure 100: 3D solid model of the plate after machining of fixing boxes in both sides.

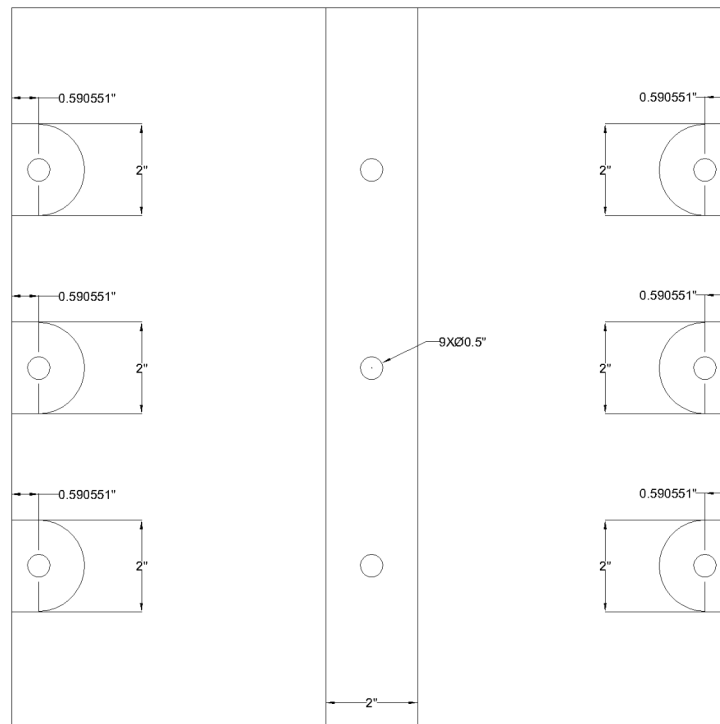


Figure 101: Schema of 0.289" & 0.124" deep boxes for further fixing.

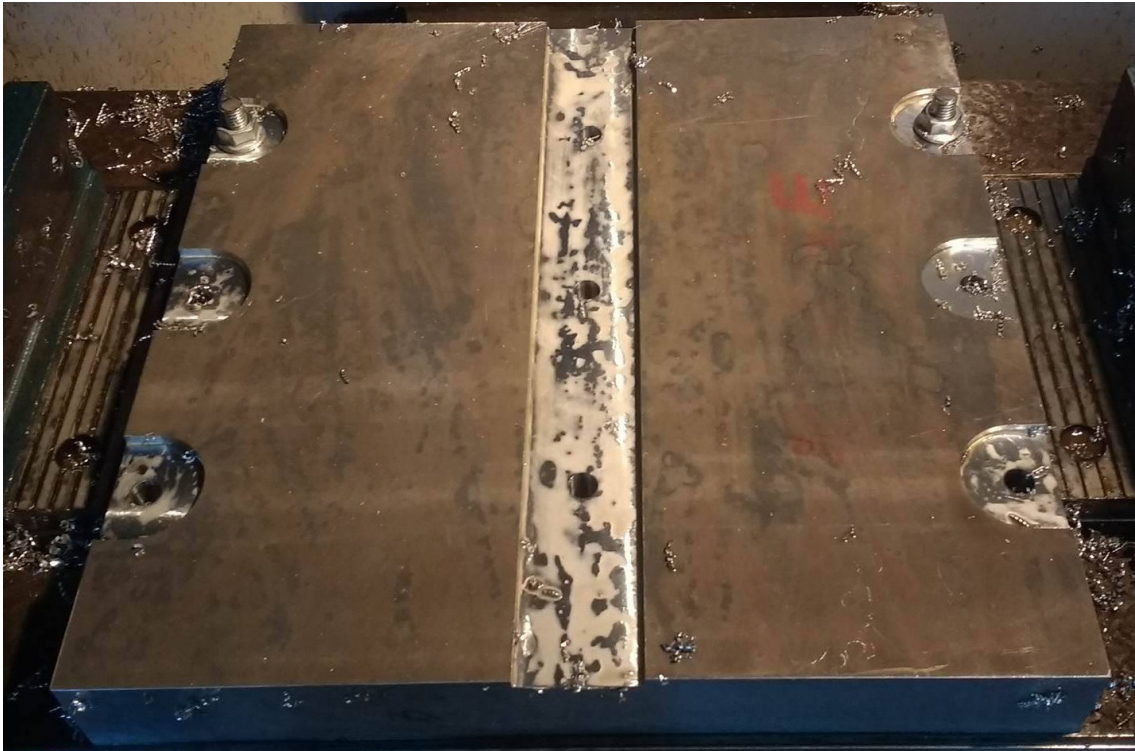


Figure 102: B3 plate after milling process for fixing boxes.

Step 3- Flattening Lower Surface of the Part

As the part is positioned 3.15 mm from the lower surface of the plate, after fixing boxes machining in both sides, the removal of the excess material at the lower surface is performed. After flattening, this surface will be the lower surface of the part. The part is fixed with the 3.15 mm boxes upwards as seen in Figure 103.

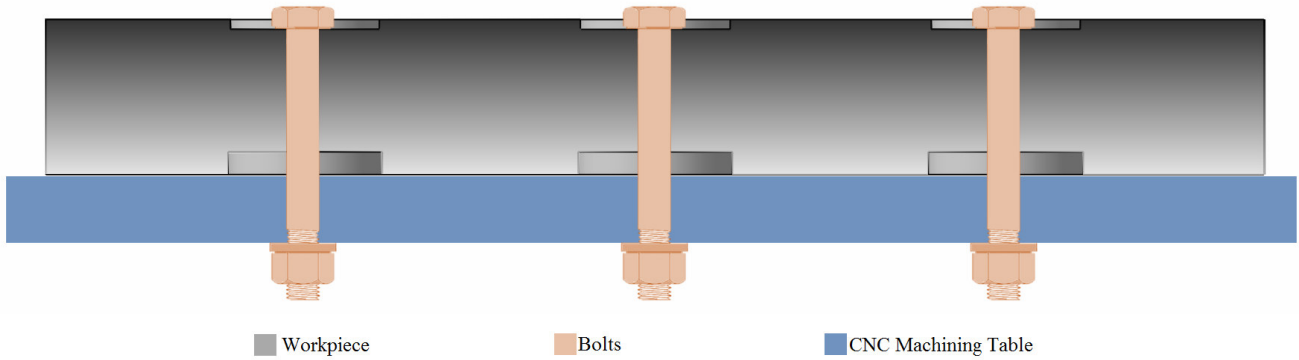


Figure 103: 2D Schematic. Fully fixing of the part before flattening machining.



Figure 104: Fully fixed B3 plate ready for flattening process.

Once fixed, the 3.15 mm material layer is removed to have the lower surface of the part totally flatted. Figure 105 shows the removal of the 10.5 mm material layer (flattening process). The mill is 4" diameter, at 91 rpm, 2 in/min feed rate and 0.04" deep by path, machining a total deep of 0.124" (3.15 mm).

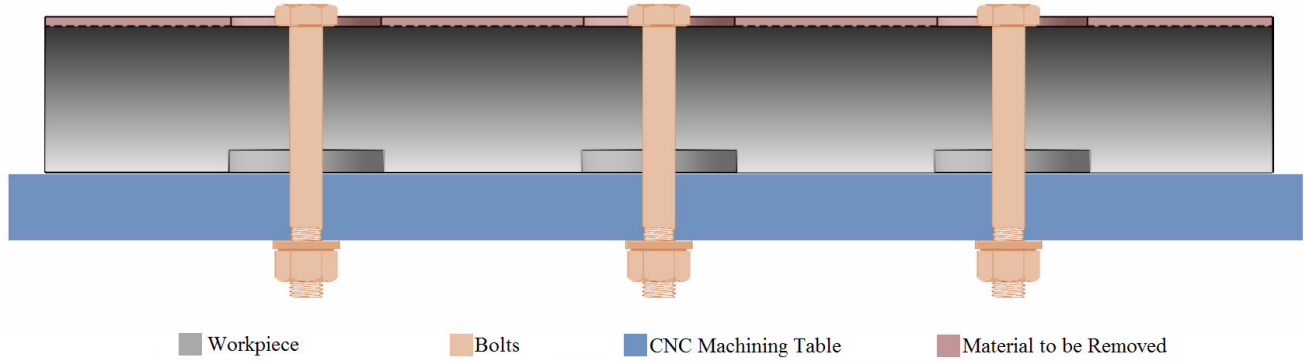


Figure 105: 2D Schema. Removal of the 3.15 mm material layer for flattening.



Figure 106: Detailed B3 part after lower surface flattening process.

Step 4- Flattening Upper Surface of the Part

After flattening the lower surface of the part, the piece was released and flipped, then it was fixed again for upper 7.35 mm layer removal before final machining. Figure 107 shows the schema of the plate once flipped and fixed.

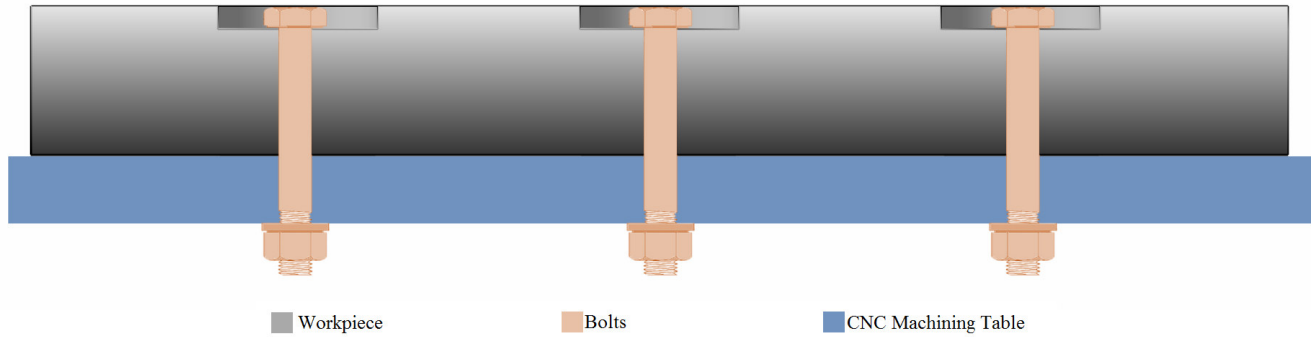


Figure 107: 2D Schematic. Fully fixing of the flipped part before flattening machining.

Once fixed, the 7.35 mm material layer is removed to have the upper surface of the part totally flattened. Figure 108 shows the removal of the 7.35 mm material layer (flattening process). The mill is 4" diameter, at 91 rpm, 2 in/min feed rate and 0.04" deep by path, machining a total deep of 0.289" (7.35 mm).

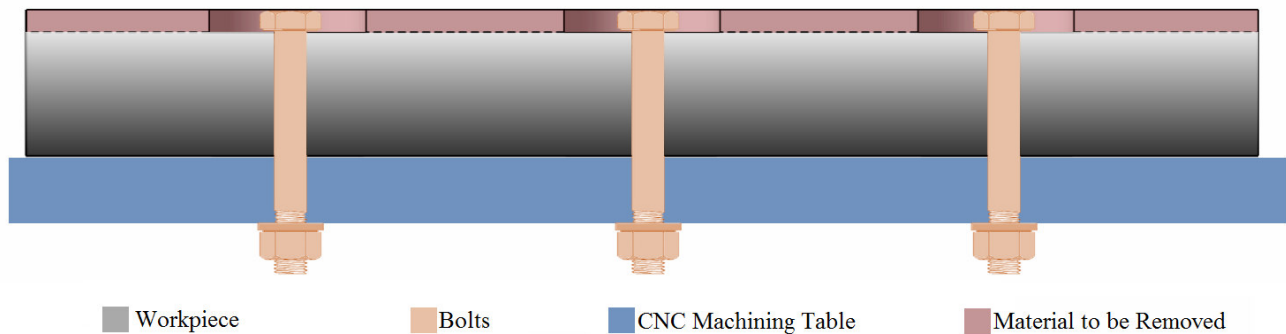


Figure 108: 2D Schema. Removal of the 7.35 mm material layer for flattening.



Figure 109: Detailed B3 part after upper surface flattening process.

Step 5- Machining of the part

The part remains fixed ensuring that the lower surface is totally flat in contact with the machining table (some distortion is expected from the previous layer removal).

Figure 110 shows an schema of the remained fixed part; the part is machined to obtain the final geometry, a 4" diameter mill is used, at 91 rpm, 2 in/min feed rate and 0.04" deep by path. Figure 111 shows the schema of the final machining process.

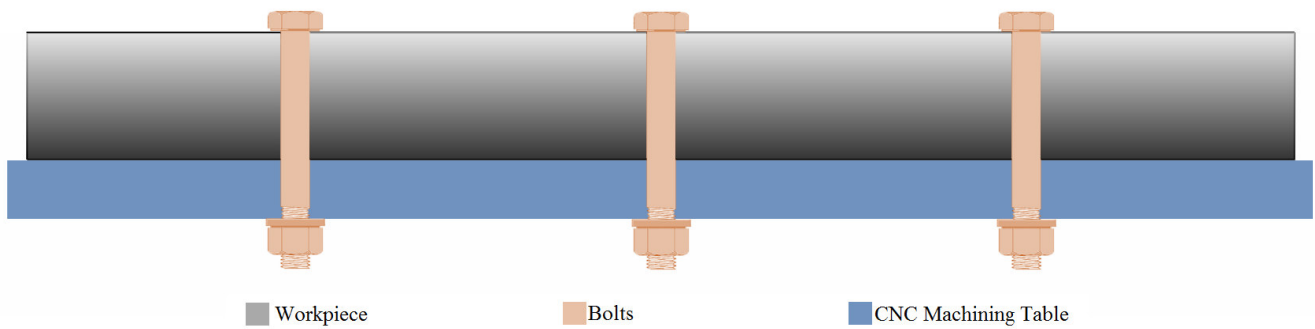


Figure 110: 2D Schema. Fully fixing of the flipped part after flattening.

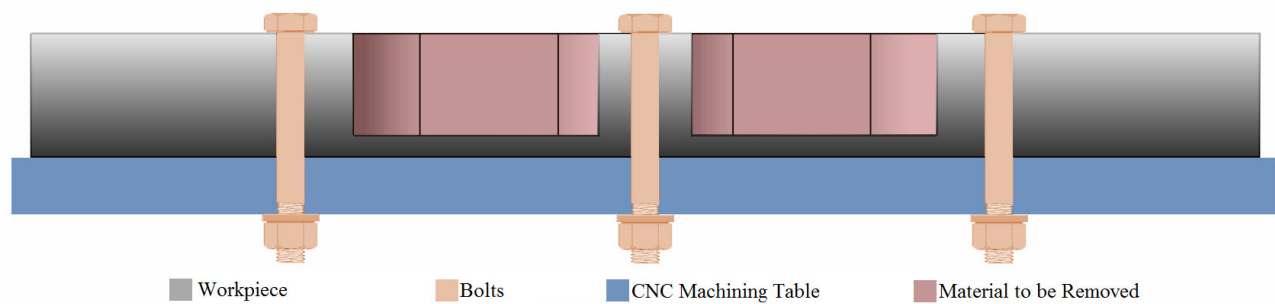


Figure 111: 2D Schema. Final machining process for proposed geometry.

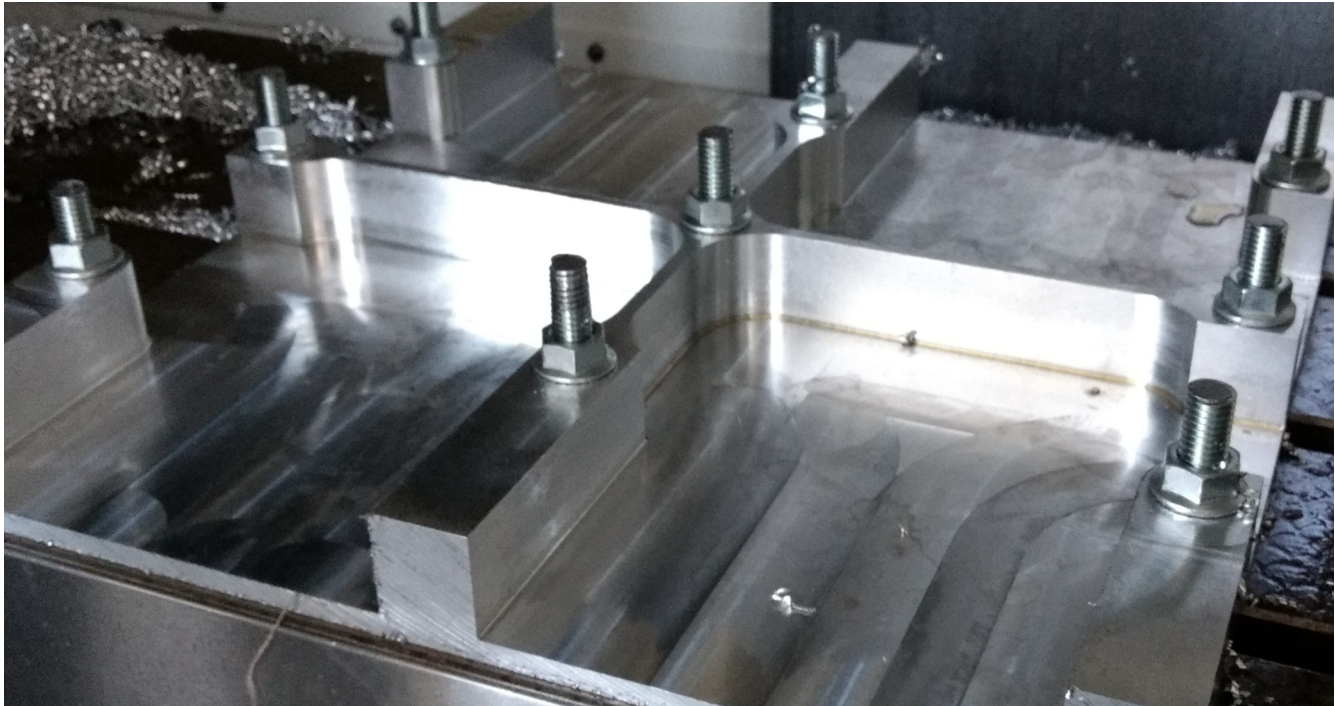


Figure 112: B3 part after machining before released, case study geometry.

Results Comparison & Validation

After machining, the parts were measured with a high accuracy 3D scan, then deviation analysis was performed into GOM Inspect open source software for Z direction.

10.5 mm Z Offset (High Distortion Position)

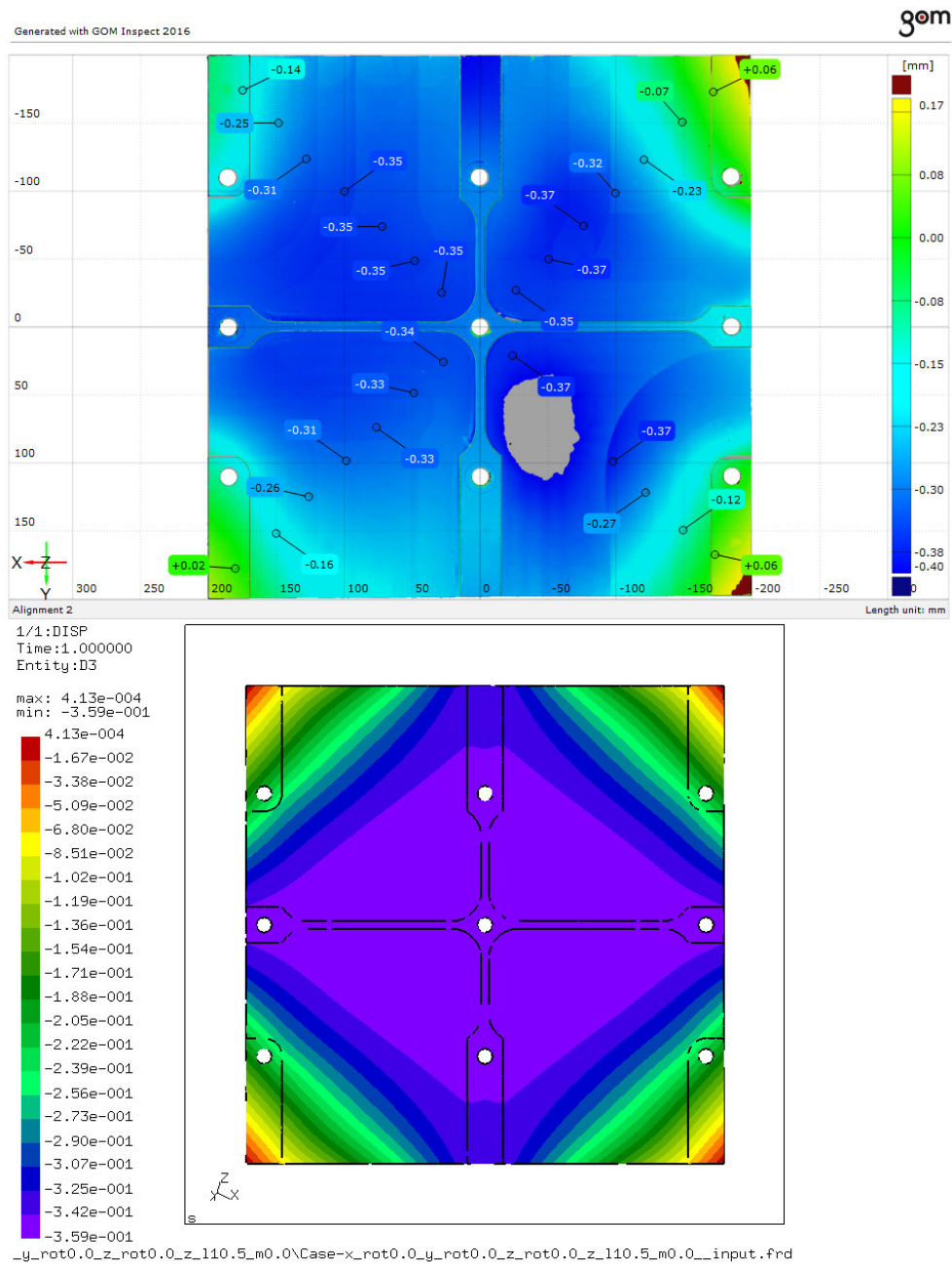


Figure 113: Top surface deviation analysis for the B2 part. 10.5 mm Z offset high distortion position. Above the deviation analysis (Original geometry vs. measurements of machined part) and below the results of simulation. Distortion in Z direction (mm).

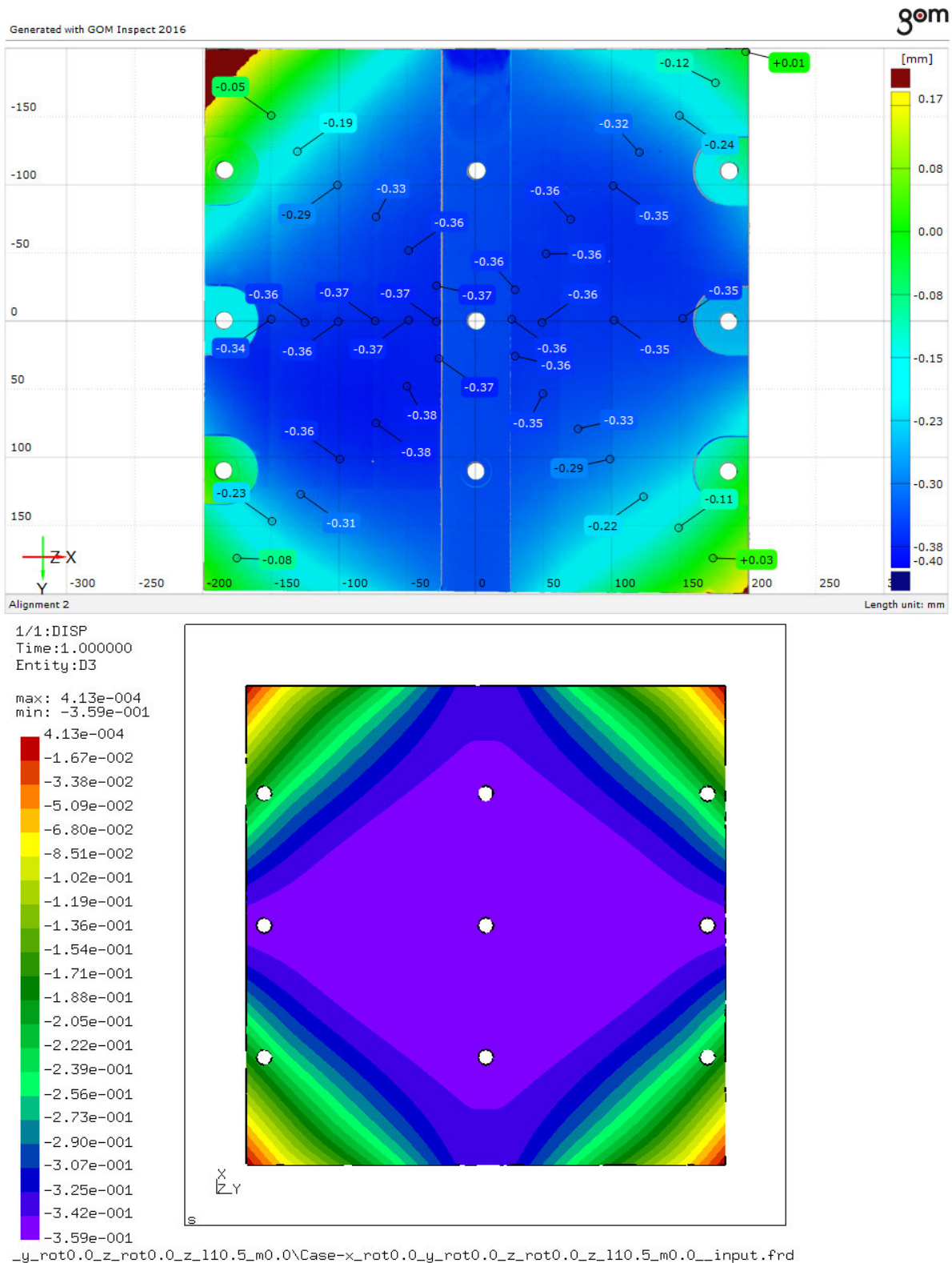
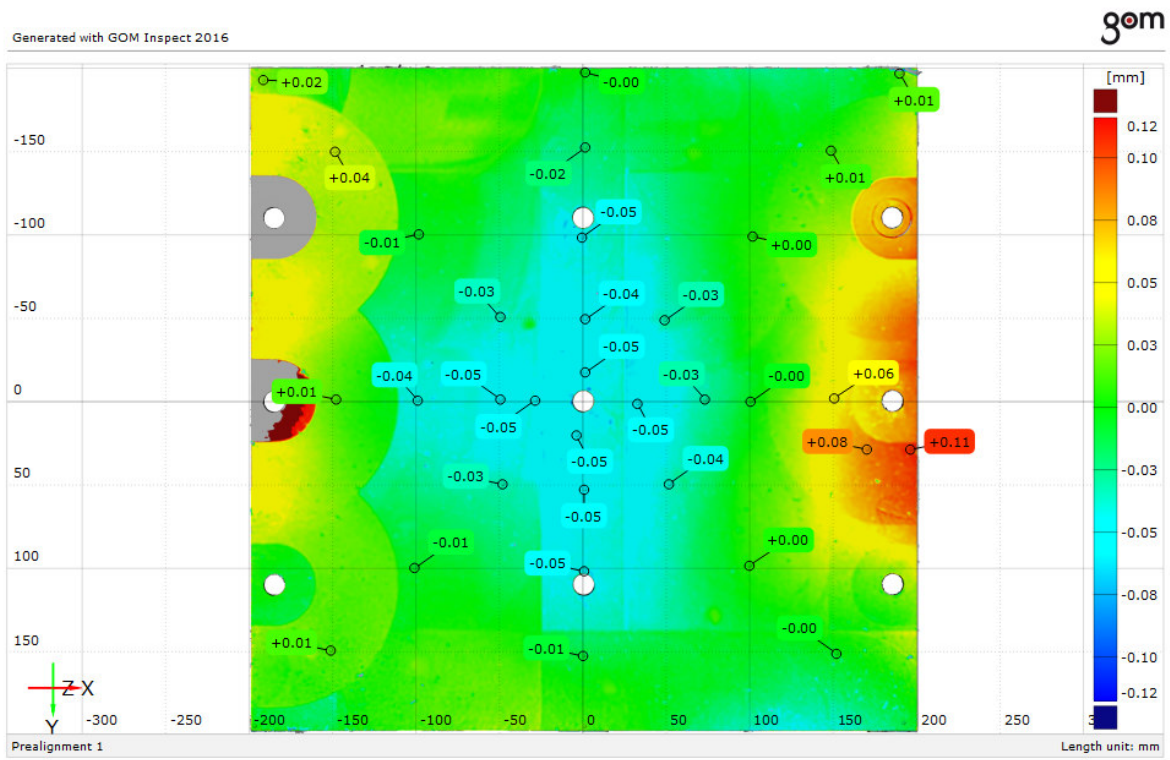


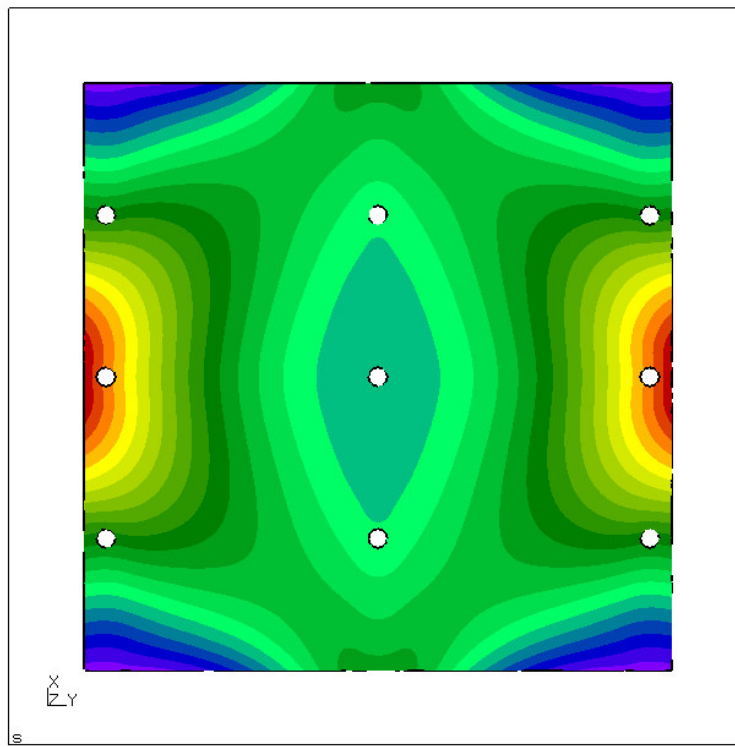
Figure 114: Bottom surface deviation analysis for the B2 part. 10.5 mm Z offset high distortion position. Above the deviation analysis (Original geometry vs. measurements of machined part) and below the results of simulation. Distortion in Z direction (mm).



1/1:DISP
Time:1.000000
Entity:D3

max: 1.26e-001
min: -3.16e-003

1.26e-001
1.20e-001
1.14e-001
1.08e-001
1.02e-001
9.55e-002
8.93e-002
8.31e-002
7.70e-002
7.08e-002
6.46e-002
5.85e-002
5.23e-002
4.61e-002
4.00e-002
3.38e-002
2.77e-002
2.15e-002
1.53e-002
9.16e-003
3.00e-003
-3.16e-003



_y_rot0.0_z_rot0.0_z_13.15_m0.0\Case-x_rot0.0_y_rot0.0_z_rot0.0_z_13.15_m0.0_input.frd

Figure 116: Bottom surface deviation analysis for the B3 part optimal position. 3.15 mm Z offset optimal position. Above the deviation analysis (Original geometry vs. measurements of machined part) and below the results of simulation. Distortion in Z direction (mm).

Comments on Results

10.5 mm Z Offset

Forth quadrant was the first into the machining process, over-machining was performed when trying to machine a previous version of the geometry which had a 3 mm lower skin thickness, unfortunately the mill can not touch the machining table, the lower distance to machine table is 7 mm, the geometry was then updated to 7 mm lower skin thickness.

There is good congruence between machined part and simulation, the deformation profile is the same, deformation sense is also the same, and distortion values are very similar, ignoring the over-machined zone at the forth quadrant of the top view, there is good symmetry.

3.15 mm Z Offset

For this position is important to analyze both sides, the top surface describes with good accuracy the deformation pattern, the deformation profile is quite similar, having most of the distortion at the lateral sides; deformation sense is the same and distortion values are very close, there is good symmetry as well.

The bottom surface describes better the central distortion profile, also with maximal distortion at the lateral sides, however due machining process sequence (Boxes for fixing before flattening) these two surface are not exactly the same, the boxes are easily seen in the deviation analysis. This is a complementary analysis for central zone, because internal structures at the top surface impede a good comparison in these zones. The deformation profile is also similar, the deformation sense is the same having similar amplitude of distortion values.

2 Levels 1/16 Fractional Factorial Design

The full report generated in R is shown in Appendix G; Figure 117 shows the histogram of the 256 results. Most results are found in low distortion values (0-0.2 mm), the experiment with maximal distortion value reaches 0.5 mm of distortion; around 90 experiments has between 0 and 0.05 mm distortion, almost half of the total number of experiments, which suggest good reliability in results.

Figure 118 reaffirms previous plot, having the median of the total experiments with 0.1 mm or less in distortion. Most of the experiments does not exceed 0.2 mm of distortion. This plot is a good way to see the confidence of the results.

Figure 119 shows the main effects of each coefficient for both, L and LT directions, all interacting in the experiments. The variables with more effects are from L direction, the coefficient C4; and for LT direction the coefficients C4 and C2. In both directions the 4th coefficient has an important influence in simulation results. It would be interesting to identify the relation of this coefficient with a manufacturing process variable, in this case, the control of this manufacturing variable would improve confidentiality of results. Figure 120 shows the coupled interactions between the variables, it is clearly seen that there are not significant interactions between any variable combination.

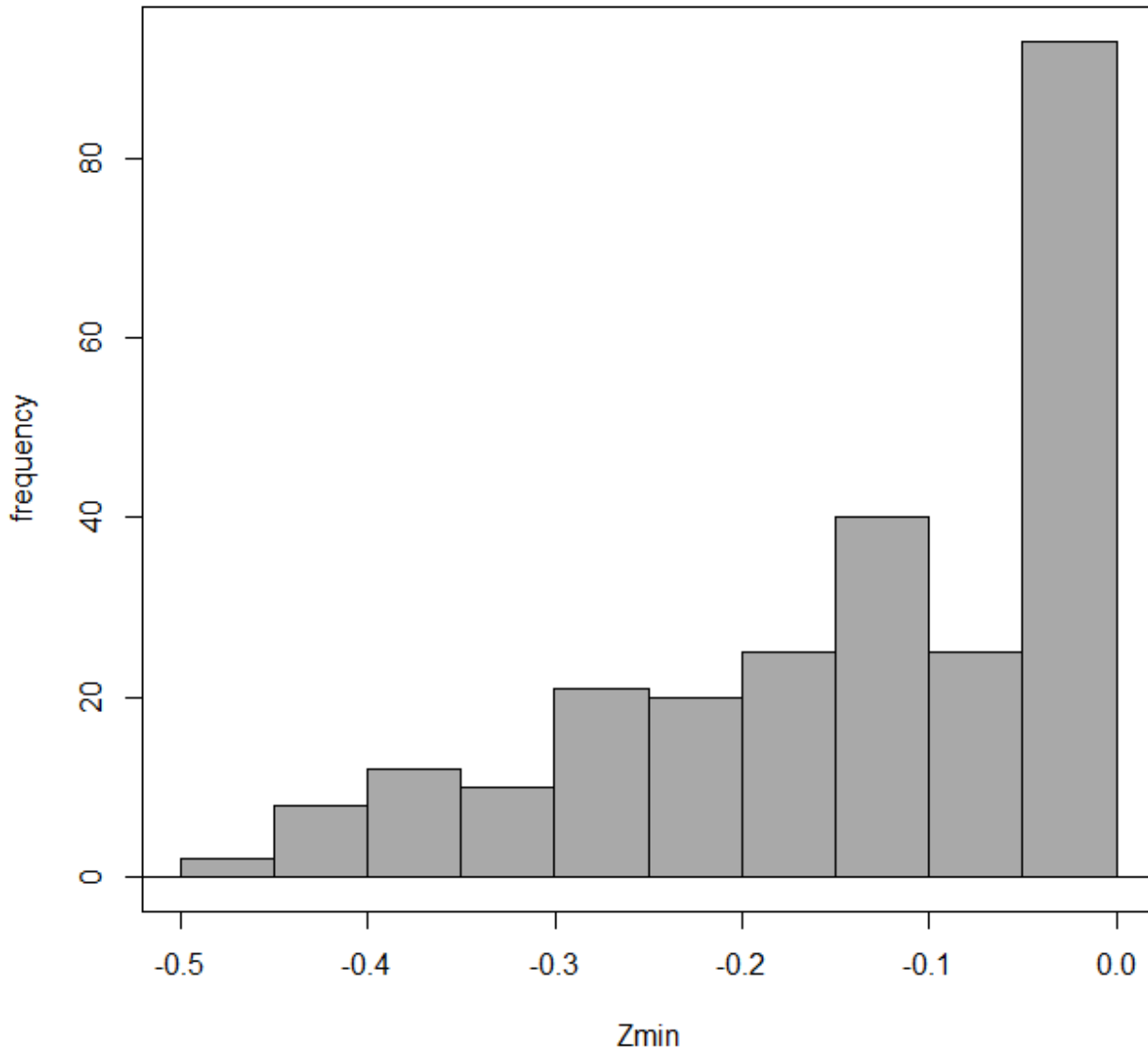


Figure 117: Histogram of the results for the 1/16 fractional factorial design of the case study.

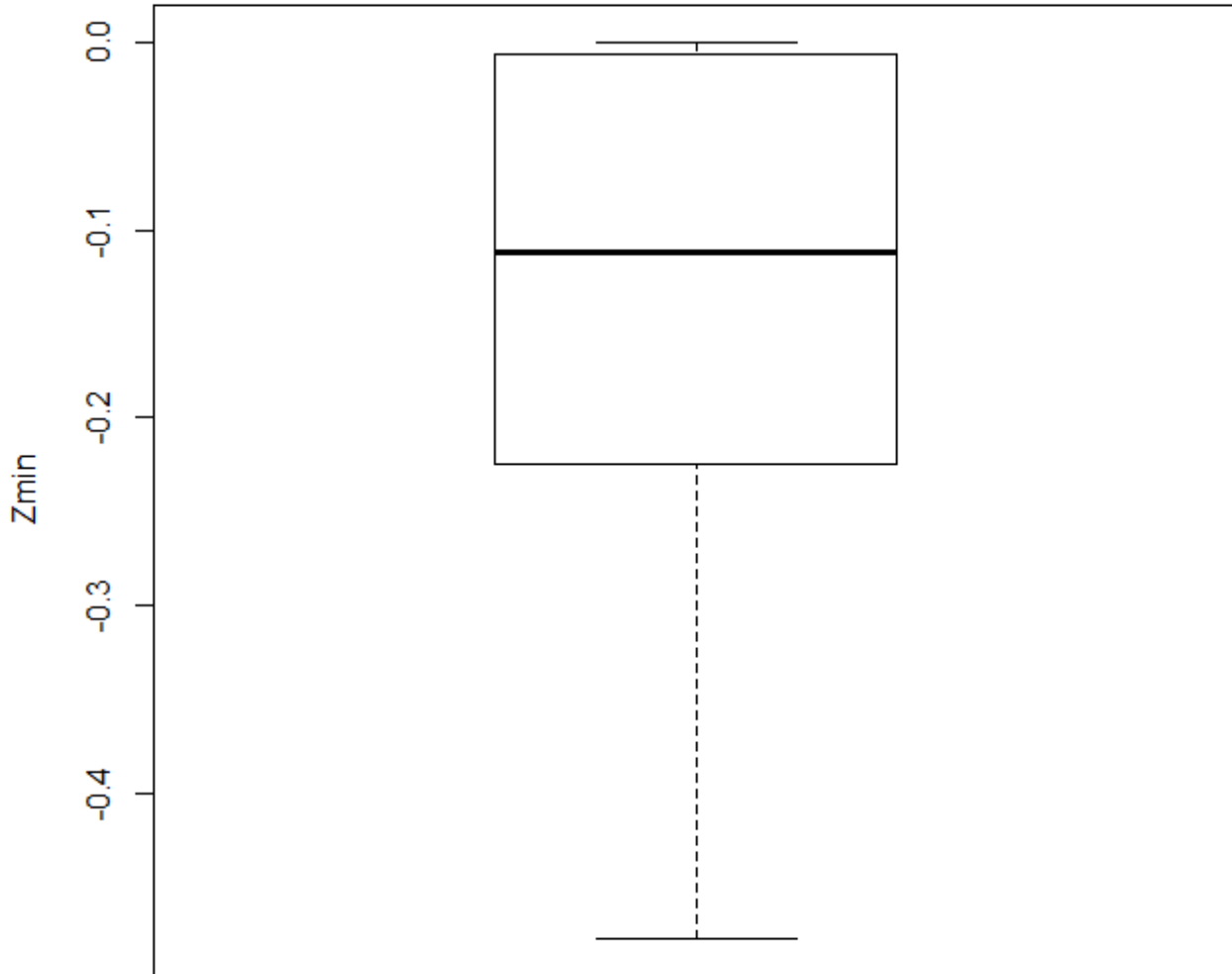


Figure 118: Box plot of the results for the 1/16 fractional factorial design of the case study.

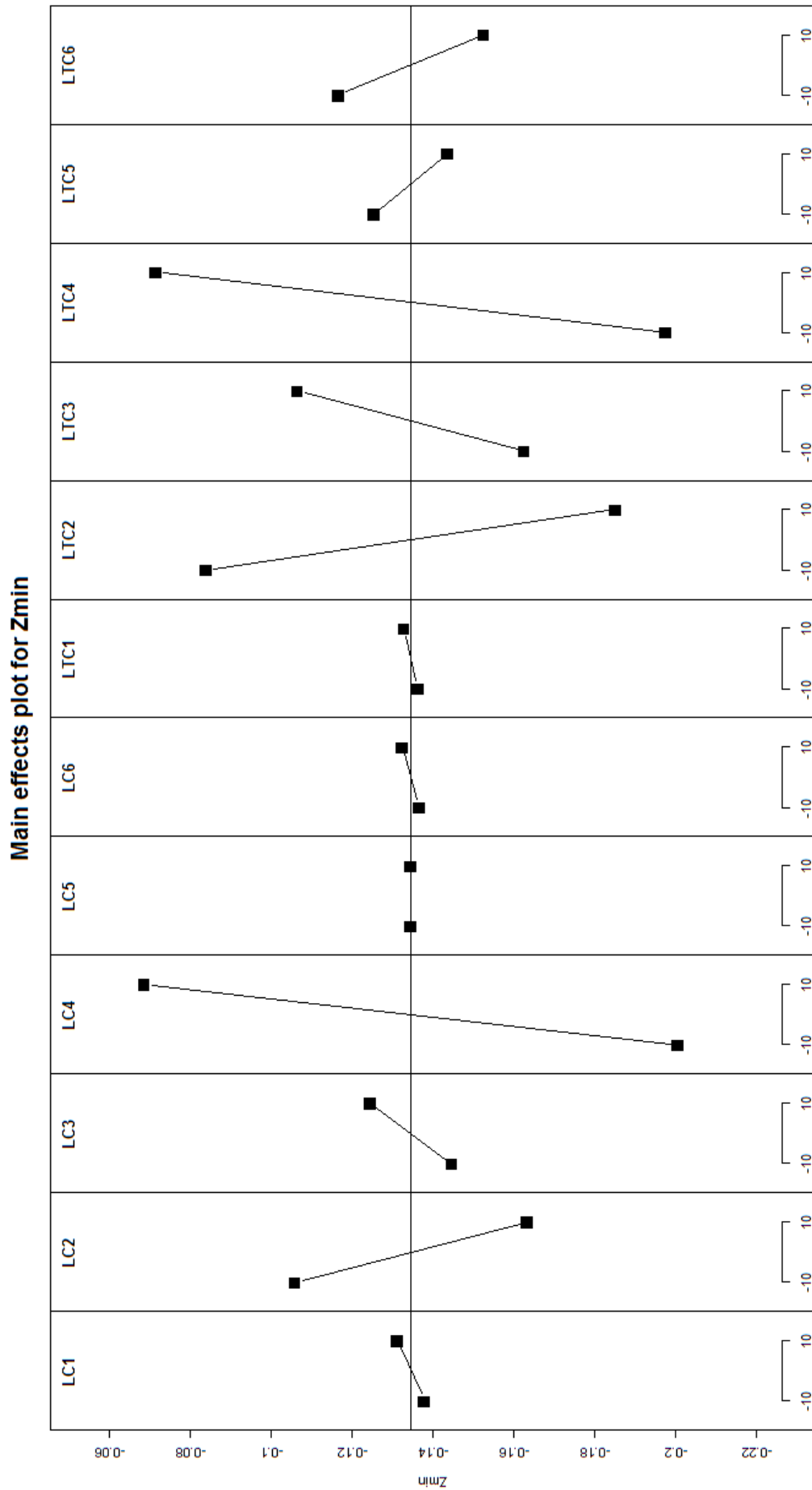


Figure 119: Main effect plot of the results for the 1/16 fractional factorial design of the case study.

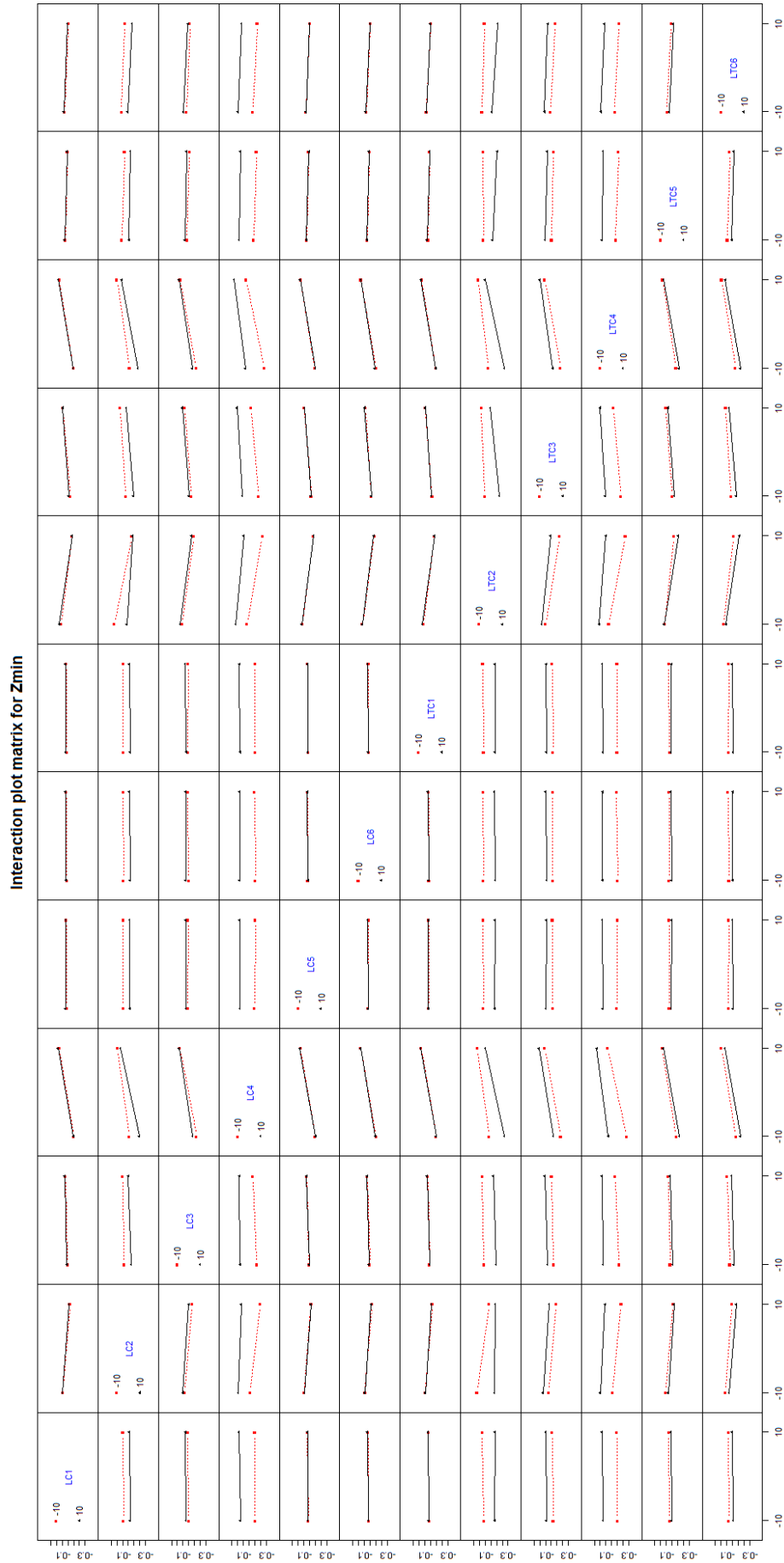


Figure 120: Interaction effect plot of the results for the 1/16 fractional factorial design of the case study.

VII Conclusions and Further Work

Distortion is a challenging problem in aerospace industry due complex and big monolithic structural components. Distortion can come from several factors from part geometry, bulk material residual stresses or induced residual stresses during the machining process. Distortion after machining can be repaired with rework processes like shot peening, which induce compressive residual stresses correcting distortion. Unfortunately, all the rework processes add manufacturing costs and lead time to the manufacturing life cycle. The theoretical bases assumes that residual stresses are homogeneous in the plane of product, meaning that residual stresses on one end of the plate should be exactly the same as the other extremity. This assumption is generally acceptable, but there is also some variation of the residual stress profiles depending on the location into the mother plate; stretching process induce some variations comparing the edges with the center of the plate, the specimens taken for residual stresses measurement are only representative to an specific location of the mother plate; however it is seen in the experimental tests that this does not really affect the predicted results; further questioning on identifying the specific location of the specimens of residual stresses measurements and location of the testing parts are required to have concise conclusions on this.

Another assumption into the simulation is that all the material is removed in one go, the work-piece is totally fixed and machined in one step. Despite it is a good assumption, the components are hardly ever machined in this way; positioning of the component into the plate, implies in some cases, removal of material from all around the plate, making impossible to totally fix it during all the operations, several steps will be performed and releasement of the part between these operations is inevitable, having distortion after each step. Further work would take this several steps, simulating every step and improving precision on prediction.

The workflow lead into a more efficient resource planning, decrease of manufacturing costs and avoid rejected parts. The time for the workflow to propose an optimized position is minimal compared to the time needed for rework processes to repair distortion and can be further decreased with improvements and optimization of the workflow. Moreover, it can be used as a "Design against Distortion" tool in the generation and improvement of new aerospace components, making possible to predict distortion pattern of a new concept structural component. Despite the tendency to machine parts from thinner plates, reducing material (this increase machining distortion and expensive reworking) , this workflow permits to choose the correct thickness of the plate and decrease manufacturing costs.

The workflow to minimize part distortion described in [11] is analyzed to implement and develop the software tools required to simplify the process. The objective of using open source software to develop the required tools was achieved, developing the modules and tools in FreeCAD, CalculiX and R; this facilitated the personalization and implementation of the specific demand that any other commercial software offers until now. This also avoids licensing and copyright infringement.

The final software provides the friendly interface and software capabilities all integrated, supporting the everyday work of the industrial engineer.

The workflow method and software were tested with the experimental Case Study; a representative part with complex shape was design to machine into the plates provided by KAISER Aluminum. The data provided from these plates was processed to obtain the information needed for the analysis. Two positions were machined, one with high distortion and the optimal position found in the analysis; the measurements of both positions show good agreement not only in deformation pattern but also in deformation values. This experiments support and validate the theoretical bases of the workflow and the software development.

The software was improved with a material analysis section; 2 levels fractional factorial designs can be generated, this permit to analyze the coefficients of the residual stress profiles and determine the influence of each one separately or interacting in couples. This software section was also tested with the most complex design ($\pm 10\%$ variation, 12 variables, 1/16 fractional factorial design) for the optimal position in the Case Study, obtaining coherent results from the analysis.

The proposed workflow was focused on rolled aluminum plates, however, the problem is extended to other materials and manufacturing process; titanium alloys are being more and more used in aerospace industry and many parts are not machined from rolled plates but also from extrusions or forgings. Composite materials are used for fuel efficiency, decreasing the weight of the aircraft; despite composites deal with part distortion, this distortion can be induced in different manufacturing steps (curing, forming, trimming, etc.).

As open source software was used for distortion prediction, a next step would be to perform the same simulations in a recognized commercial FEM software (ANSYS or Abaqus), these softwares are frequently tested and improved, decreasing the possibility to any internal error in the software; these commercial softwares are supported and guaranteed. Results in these commercial software would be compared, identifying any possible error or deficiency in the developed FreeCAD module or CalculiX stress mapping code for final validation.

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Appendix

A: Case Study Geometry Plane

B: Material Properties Input File

C: 2 Levels Fractional Factorial Designs

D: SIGINI Fortran Code for stress mapping

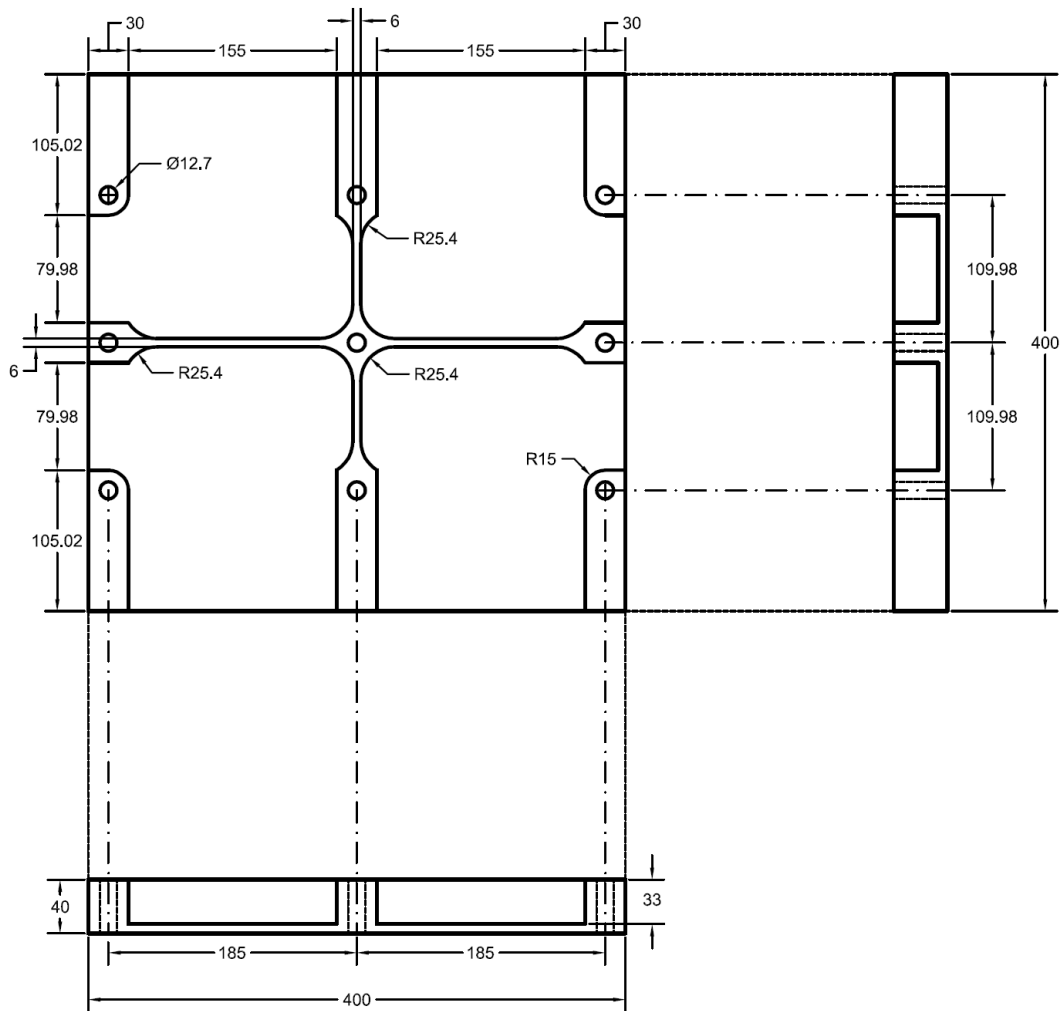
E: CalculiX GraphiX (cgx) Case Study Results

F: Output .csv Format Table of Case Study Results

G: R Positioning Output of Case Study Results

H: R Output of the 1/16 Fractional Factorial Design for the Case Study

A: Case Study Geometry Plane



University of Guanajuato

An Industrial Workflow to Minimize Part Distortion for Machining of Large Monolithic Components in Aerospace Industry

Drawn by
Leonardo Fermin
Barcenas Gomez

Geometry for the
Case Study

Scale: 1:5 mm

Date: 25/09/2016

Plane No. : 1

Figure 121: Plane of the representative geometry of the case study

B: Material Properties Input File

Next figure shows the basic format for residual stress input .txt file, it is the result of a fitting curve process, it contains the fitting process information and most important the global residual stress curve fit from the data analysis, C0, C1, C2, C3, C4, C5 and C6 coefficients, one file for each direction must be available, it is also possible to introduce the values manually into the software.

```

Residual Stress - Notepad
File Edit Format View Help
Tolerance on integral=0.1
Envelope drawn at +/- 3*sigma
To modify please edit R-code

=====
Local residual stress curve fits
=====

Residual stress curve 1 fit
-----
MSE:      MSE value
Integral:
  the integral value of this fit is value
  The condition on the integral is rejected
Normality:
  Normality of residuals of this fit is accepted
This fit is rejected

Residual stress curve 2 fit
-----
MSE:      MSE value
Integral:
  the integral value of this fit is value
  The condition on the integral is validated
Normality:
  Normality of residuals of this fit is accepted
This fit is valid

Residual stress curve 3 fit
-----
MSE:      MSE value
Integral:
  the integral value of this fit is value
  The condition on the integral is validated
Normality:
  Normality of residuals of this fit is accepted
This fit is valid

-----
valid residuals stress curves id are 2 3
-----

Global Residual stress curve fit
=====
Fit function: s = c0+ c1*cos(2*pi*y) + c2*cos(2*pi*2*y) + c3*cos(2*pi*3*y) + c4*cos(2*pi*4*y) + c5*cos(2*pi*5*y)
with s = stress and y = position in thickness, normalised w.r.t. total thickness
c0 to c5:
  C0 Coefficient Value
  C1 Coefficient Value
  C2 Coefficient Value
  C3 Coefficient Value
  C4 Coefficient Value
  C5 Coefficient Value
MSE:      MSE value
Integral:
  the integral value of this fit is value
  The condition on the integral is rejected
Normality:
  Normality of residuals of this fit is accepted
This fit is rejected

warning message:
In ks.test(res.stand, "pnorm", mean = 0, sd = 1) :
  cannot compute correct p-values with ties

```

Figure 122: Input file for residual stress coefficients

C: 2 Levels Fractional Factorial Designs

2 Coefficients, 2 levels, Full Factorial Design

GENERAL DESIGN INFORMATION
 Experimental design of type full factorial
 4 runs

Design		
Run	A	B
1	-1	-1
2	1	-1
3	-1	1
4	1	1

3 Coefficients, 2 levels, Full Factorial Design

GENERAL DESIGN INFORMATION
 Experimental design of type full factorial
 8 runs

Design			
Run	A	B	C
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1

4 Coefficients, 2 levels, Full Factorial Design

GENERAL DESIGN INFORMATION
 Experimental design of type full factorial
 16 runs

Design				
Run	A	B	C	D
1	-1	-1	-1	-1
2	1	-1	-1	-1
3	-1	1	-1	-1
4	1	1	-1	-1
5	-1	-1	1	-1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	-1
9	-1	-1	-1	1
10	1	-1	-1	1
11	-1	1	-1	1
12	1	1	-1	1
13	-1	-1	1	1
14	1	-1	1	1
15	-1	1	1	1
16	1	1	1	1

4 Coefficients, 2 levels, 1/2 Fractional Factorial Design

GENERAL DESIGN INFORMATION
 8 runs, 4 factors,
 Resolution IV

Design generating information:
 Generators
 D=ABC

WARNING
 CONFOUNDING
 AB=CD AC=BD AD=BC

Design				
Run	A	B	C	D
1	-1	-1	-1	-1
2	1	-1	-1	1
3	-1	1	-1	1
4	1	1	-1	-1
5	-1	-1	1	1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	1

5 Coefficients, 2 levels, 1/2 Fractional Factorial Design

GENERAL DESIGN INFORMATION

16 runs, 5 factors,

Resolution V

Design generating information:

Generators

E=ABCD

Design					
Run	A	B	C	D	E
1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	-1
4	1	1	-1	-1	1
5	-1	-1	1	-1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	1
8	1	1	1	-1	-1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1

5 Coefficients, 2 levels, 1/4 Fractional Factorial Design

GENERAL DESIGN INFORMATION

8 runs, 5 factors,

Resolution III

Design generating information:

Generators

D=AB E=AC

WARNING

CONFOUNDING

A=BD=CE B=AD C=AE D=AB E=AC

BC=DE BE=CD

Design					
Run	A	B	C	D	E
1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	1
4	1	1	-1	1	-1
5	-1	-1	1	1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	-1
8	1	1	1	1	1

6 Coefficients, 2 levels, 1/2 Fractional Factorial Design

GENERAL DESIGN INFORMATION

32 runs, 6 factors,

Resolution VI

Design generating information:

Generators

F=ABCDE

Design						
Run	A	B	C	D	E	F
1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	-1	1
3	-1	1	-1	-1	-1	1
4	1	1	-1	-1	-1	-1
5	-1	-1	1	-1	-1	1
6	1	-1	1	-1	-1	-1
7	-1	1	1	-1	-1	-1
8	1	1	1	-1	-1	1
9	-1	-1	-1	1	-1	1
10	1	-1	-1	1	-1	-1
11	-1	1	-1	1	-1	-1
12	1	1	-1	1	-1	1
13	-1	-1	1	1	-1	-1
14	1	-1	1	1	-1	1
15	-1	1	1	1	-1	1
16	1	1	1	1	-1	-1
17	-1	-1	-1	-1	1	1
18	1	-1	-1	-1	1	-1
19	-1	1	-1	-1	1	-1
20	1	1	-1	-1	1	1
21	-1	-1	1	-1	1	-1
22	1	-1	1	-1	1	1
23	-1	1	1	-1	1	1
24	1	1	1	-1	1	-1
25	-1	-1	-1	1	1	-1
26	1	-1	-1	1	1	1
27	-1	1	-1	1	1	1
28	1	1	-1	1	1	-1
29	-1	-1	1	1	1	1
30	1	-1	1	1	1	-1
31	-1	1	1	1	1	-1
32	1	1	1	1	1	1

6 Coefficients, 2 levels, 1/4 Fractional Factorial Design

GENERAL DESIGN INFORMATION

16 runs, 6 factors,
Resolution IV

Design generating information:

E=ABC F=ABD

WARNING

CONFOUNDING

AB=CE=DF AC=BE AD=BF AE=BC AF=BD CD=EF CF=DE

Design						
Run	A	B	C	D	E	F
1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1	1
3	-1	1	-1	-1	1	1
4	1	1	-1	-1	-1	-1
5	-1	-1	1	-1	1	-1
6	1	-1	1	-1	-1	1
7	-1	1	1	-1	-1	1
8	1	1	1	-1	1	-1
9	-1	-1	-1	1	-1	1
10	1	-1	-1	1	1	-1
11	-1	1	-1	1	1	-1
12	1	1	-1	1	-1	1
13	-1	-1	1	1	1	1
14	1	-1	1	1	-1	-1
15	-1	1	1	1	-1	-1
16	1	1	1	1	1	1

7 Coefficients, 2 levels, 1/2 Fractional Factorial Design

GENERAL DESIGN INFORMATION

64 runs, 7 factors,

Resolution VII

Design generating information:

Generators

G=ABCDEF

Design							
Run	A	B	C	D	E	F	G
1	-1	-1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	-1
4	1	1	-1	-1	-1	-1	1
5	-1	-1	1	-1	-1	-1	-1
6	1	-1	1	-1	-1	-1	1
7	-1	1	1	-1	-1	-1	1
8	1	1	1	-1	-1	-1	-1
9	-1	-1	-1	1	-1	-1	-1
10	1	-1	-1	1	-1	-1	1
11	-1	1	-1	1	-1	-1	1
12	1	1	-1	1	-1	-1	-1
13	-1	-1	1	1	-1	-1	1
14	1	-1	1	1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1
16	1	1	1	1	-1	-1	1
17	-1	-1	-1	-1	1	-1	-1
18	1	-1	-1	-1	1	-1	1
19	-1	1	-1	-1	1	-1	1
20	1	1	-1	-1	1	-1	-1
21	-1	-1	1	-1	1	-1	1
22	1	-1	1	-1	1	-1	-1
23	-1	1	1	-1	1	-1	-1
24	1	1	1	-1	1	-1	1
25	-1	-1	-1	1	1	-1	1
26	1	-1	-1	1	1	-1	-1
27	-1	1	-1	1	1	-1	-1
28	1	1	-1	1	1	-1	1
29	-1	-1	1	1	1	-1	-1
30	1	-1	1	1	1	-1	1

Design							
Run	A	B	C	D	E	F	G
31	-1	1	1	1	1	-1	1
32	1	1	1	1	1	-1	-1
33	-1	-1	-1	-1	-1	1	-1
34	1	-1	-1	-1	-1	1	1
35	-1	1	-1	-1	-1	1	1
36	1	1	-1	-1	-1	1	-1
37	-1	-1	1	-1	-1	1	1
38	1	-1	1	-1	-1	1	-1
39	-1	1	1	-1	-1	1	-1
40	1	1	1	-1	-1	1	1
41	-1	-1	-1	1	-1	1	1
42	1	-1	-1	1	-1	1	-1
43	-1	1	-1	1	-1	1	-1
44	1	1	-1	1	-1	1	1
45	-1	-1	1	1	-1	1	-1
46	1	-1	1	1	-1	1	1
47	-1	1	1	1	-1	1	1
48	1	1	1	1	-1	1	-1
49	-1	-1	-1	-1	1	1	1
50	1	-1	-1	-1	1	1	-1
51	-1	1	-1	-1	1	1	-1
52	1	1	-1	-1	1	1	1
53	-1	-1	1	-1	1	1	-1
54	1	-1	1	-1	1	1	1
55	-1	1	1	-1	1	1	1
56	1	1	1	-1	1	1	-1
57	-1	-1	-1	1	1	1	-1
58	1	-1	-1	1	1	1	1
59	-1	1	-1	1	1	1	1
60	1	1	-1	1	1	1	-1
61	-1	-1	1	1	1	1	1
62	1	-1	1	1	1	1	-1
63	-1	1	1	1	1	1	-1
64	1	1	1	1	1	1	1

7 Coefficients, 2 levels, 1/4 Fractional Factorial Design

GENERAL DESIGN INFORMATION

32 runs, 7 factors,
Resolution IV

Design generating information:

Generators

F=ABC G=ABDE

WARNING

CONFOUNDING

AB=CF AC=BF AF=BC

Design							
Run	A	B	C	D	E	F	G
1	-1	-1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	1	-1
3	-1	1	-1	-1	-1	1	-1
4	1	1	-1	-1	-1	-1	1
5	-1	-1	1	-1	-1	1	1
6	1	-1	1	-1	-1	-1	-1
7	-1	1	1	-1	-1	-1	-1
8	1	1	1	-1	-1	1	1
9	-1	-1	-1	1	-1	-1	-1
10	1	-1	-1	1	-1	1	1
11	-1	1	-1	1	-1	1	1
12	1	1	-1	1	-1	-1	-1
13	-1	-1	1	1	-1	1	-1
14	1	-1	1	1	-1	-1	1
15	-1	1	1	1	-1	-1	1
16	1	1	1	1	-1	1	-1
17	-1	-1	-1	-1	1	-1	-1
18	1	-1	-1	-1	1	1	1
19	-1	1	-1	-1	1	1	1
20	1	1	-1	-1	1	-1	-1
21	-1	-1	1	-1	1	1	-1
22	1	-1	1	-1	1	-1	1
23	-1	1	1	-1	1	-1	1
24	1	1	1	-1	1	1	-1
25	-1	-1	-1	1	1	-1	1
26	1	-1	-1	1	1	1	-1
27	-1	1	-1	1	1	1	-1
28	1	1	-1	1	1	-1	1
29	-1	-1	1	1	1	1	1
30	1	-1	1	1	1	-1	-1
31	-1	1	1	1	1	-1	-1
32	1	1	1	1	1	1	1

7 Coefficients, 2 levels, 1/8 Fractional Factorial Design

GENERAL DESIGN INFORMATION

16 runs, 7 factors,
Resolution IV

Design generating information:

Generators

E=ABC F=ABD G=ACD

WARNING

CONFOUNDING

AB=CE=DF AC=BE=DG AD=BF=CG

AE=BC=FG AF=BD=EG AG=CD=EF BG=CF=DE

Design							
Run	A	B	C	D	E	F	G
1	-1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1	1	1
3	-1	1	-1	-1	1	1	-1
4	1	1	-1	-1	-1	-1	1
5	-1	-1	1	-1	1	-1	1
6	1	-1	1	-1	-1	1	-1
7	-1	1	1	-1	-1	1	1
8	1	1	1	-1	1	-1	-1
9	-1	-1	-1	1	-1	1	1
10	1	-1	-1	1	1	-1	-1
11	-1	1	-1	1	1	-1	1
12	1	1	-1	1	-1	1	-1
13	-1	-1	1	1	1	1	-1
14	1	-1	1	1	-1	-1	1
15	-1	1	1	1	-1	-1	-1
16	1	1	1	1	1	1	1

8 Coefficients, 2 levels, 1/2 Fractional Factorial Design

GENERAL DESIGN INFORMATION

128 runs, 8 factors,
Resolution VIII

Design generating information:

Generators

H=ABCDEFG

Design								
Run	A	B	C	D	E	F	G	H
1	-1	-1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	-1	-1	-1	1
3	-1	1	-1	-1	-1	-1	-1	1
4	1	1	-1	-1	-1	-1	-1	-1
5	-1	-1	1	-1	-1	-1	-1	1
6	1	-1	1	-1	-1	-1	-1	-1
7	-1	1	1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	-1	1
9	-1	-1	-1	1	-1	-1	-1	1
10	1	-1	-1	1	-1	-1	-1	-1
11	-1	1	-1	1	-1	-1	-1	-1
12	1	1	-1	1	-1	-1	-1	1
13	-1	-1	1	1	-1	-1	-1	-1
14	1	-1	1	1	-1	-1	-1	1
15	-1	1	1	1	-1	-1	-1	1
16	1	1	1	1	-1	-1	-1	-1
17	-1	-1	-1	-1	1	-1	-1	1
18	1	-1	-1	-1	1	-1	-1	-1
19	-1	1	-1	-1	1	-1	-1	-1
20	1	1	-1	-1	1	-1	-1	1
21	-1	-1	1	-1	1	-1	-1	-1
22	1	-1	1	-1	1	-1	-1	1
23	-1	1	1	-1	1	-1	-1	1
24	1	1	1	-1	1	-1	-1	-1
25	-1	-1	-1	1	1	-1	-1	-1
26	1	-1	-1	1	1	-1	-1	1
27	-1	1	-1	1	1	-1	-1	1
28	1	1	-1	1	1	-1	-1	-1
29	-1	-1	1	1	1	-1	-1	1
30	1	-1	1	1	1	-1	-1	-1
31	-1	1	1	1	1	-1	-1	-1
32	1	1	1	1	1	-1	-1	1
33	-1	-1	-1	-1	-1	1	-1	1
34	1	-1	-1	-1	-1	1	-1	-1
35	-1	1	-1	-1	-1	1	-1	-1
36	1	1	-1	-1	-1	1	-1	1
37	-1	-1	1	-1	-1	1	-1	-1
38	1	-1	1	-1	-1	1	-1	1
39	-1	1	1	-1	-1	1	-1	1
40	1	1	1	-1	-1	1	-1	-1

Design								
Run	A	B	C	D	E	F	G	H
41	-1	-1	-1	1	-1	1	-1	-1
42	1	-1	-1	1	-1	1	-1	1
43	-1	1	-1	1	-1	1	-1	1
44	1	1	-1	1	-1	1	-1	-1
45	-1	-1	1	1	-1	1	-1	1
46	1	-1	1	1	-1	1	-1	-1
47	-1	1	1	1	-1	1	-1	-1
48	1	1	1	1	-1	1	-1	1
49	-1	-1	-1	-1	1	1	-1	-1
50	1	-1	-1	-1	1	1	-1	1
51	-1	1	-1	-1	1	1	-1	1
52	1	1	-1	-1	1	1	-1	-1
53	-1	-1	1	-1	1	1	-1	1
54	1	-1	1	-1	1	1	-1	-1
55	-1	1	1	-1	1	1	-1	-1
56	1	1	1	-1	1	1	-1	1
57	-1	-1	-1	1	1	1	-1	1
58	1	-1	-1	1	1	1	-1	-1
59	-1	1	-1	1	1	1	-1	-1
60	1	1	-1	1	1	1	-1	1
61	-1	-1	1	1	1	1	-1	-1
62	1	-1	1	1	1	1	-1	1
63	-1	1	1	1	1	1	-1	1
64	1	1	1	1	1	1	-1	-1
65	-1	-1	-1	-1	-1	-1	1	1
66	1	-1	-1	-1	-1	-1	1	-1
67	-1	1	-1	-1	-1	-1	1	-1
68	1	1	-1	-1	-1	-1	1	1
69	-1	-1	1	-1	-1	-1	1	-1
70	1	-1	1	-1	-1	-1	1	1
71	-1	1	1	-1	-1	-1	1	1
72	1	1	1	-1	-1	-1	1	-1
73	-1	-1	-1	1	-1	-1	1	-1
74	1	-1	-1	1	-1	-1	1	1
75	-1	1	-1	1	-1	-1	1	1
76	1	1	-1	1	-1	-1	1	-1
77	-1	-1	1	1	-1	-1	1	1
78	1	-1	1	1	-1	-1	1	-1
79	-1	1	1	1	-1	-1	1	-1
80	1	1	1	1	-1	-1	1	1
81	-1	-1	-1	-1	1	-1	1	-1
82	1	-1	-1	-1	1	-1	1	1
83	-1	1	-1	-1	1	-1	1	1
84	1	1	-1	-1	1	-1	1	-1
85	-1	-1	1	-1	1	-1	1	1
86	1	-1	1	-1	1	-1	1	-1
87	-1	1	1	-1	1	-1	1	-1
88	1	1	1	-1	1	-1	1	1
89	-1	-1	-1	1	1	-1	1	1
90	1	-1	-1	1	1	-1	1	-1

Design								
Run	A	B	C	D	E	F	G	H
91	-1	1	-1	1	1	-1	1	-1
92	1	1	-1	1	1	-1	1	1
93	-1	-1	1	1	1	-1	1	-1
94	1	-1	1	1	1	-1	1	1
95	-1	1	1	1	1	-1	1	1
96	1	1	1	1	1	-1	1	-1
97	-1	-1	-1	-1	-1	1	1	-1
98	1	-1	-1	-1	-1	1	1	1
99	-1	1	-1	-1	-1	1	1	1
100	1	1	-1	-1	-1	1	1	-1
101	-1	-1	1	-1	-1	1	1	1
102	1	-1	1	-1	-1	1	1	-1
103	-1	1	1	-1	-1	1	1	-1
104	1	1	1	-1	-1	1	1	1
105	-1	-1	-1	1	-1	1	1	1
106	1	-1	-1	1	-1	1	1	-1
107	-1	1	-1	1	-1	1	1	-1
108	1	1	-1	1	-1	1	1	1
109	-1	-1	1	1	-1	1	1	-1
110	1	-1	1	1	-1	1	1	1
111	-1	1	1	1	-1	1	1	1
112	1	1	1	1	-1	1	1	-1
113	-1	-1	-1	-1	1	1	1	1
114	1	-1	-1	-1	1	1	1	-1
115	-1	1	-1	-1	1	1	1	-1
116	1	1	-1	-1	1	1	1	1
117	-1	-1	1	-1	1	1	1	-1
118	1	-1	1	-1	1	1	1	1
119	-1	1	1	-1	1	1	1	1
120	1	1	1	-1	1	1	1	-1
121	-1	-1	-1	1	1	1	1	-1
122	1	-1	-1	1	1	1	1	1
123	-1	1	-1	1	1	1	1	1
124	1	1	-1	1	1	1	1	-1
125	-1	-1	1	1	1	1	1	1
126	1	-1	1	1	1	1	1	-1
127	-1	1	1	1	1	1	1	-1
128	1	1	1	1	1	1	1	1

8 Coefficients, 2 levels, 1/4 Fractional Factorial Design

GENERAL DESIGN INFORMATION

64 runs, 8 factors,
Resolution V

Design generating information:

Generators

G=ABCD H=ABEF

Design								
Run	A	B	C	D	E	F	G	H
1	-1	-1	-1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	-1	-1
4	1	1	-1	-1	-1	-1	1	1
5	-1	-1	1	-1	-1	-1	-1	1
6	1	-1	1	-1	-1	-1	1	-1
7	-1	1	1	-1	-1	-1	1	-1
8	1	1	1	-1	-1	-1	-1	1
9	-1	-1	-1	1	-1	-1	-1	1
10	1	-1	-1	1	-1	-1	1	-1
11	-1	1	-1	1	-1	-1	1	-1
12	1	1	-1	1	-1	-1	-1	1
13	-1	-1	1	1	-1	-1	1	1
14	1	-1	1	1	-1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1	-1
16	1	1	1	1	-1	-1	1	1
17	-1	-1	-1	-1	1	-1	1	-1
18	1	-1	-1	-1	1	-1	-1	1
19	-1	1	-1	-1	1	-1	-1	1
20	1	1	-1	-1	1	-1	1	-1
21	-1	-1	1	-1	1	-1	-1	-1
22	1	-1	1	-1	1	-1	1	1
23	-1	1	1	-1	1	-1	1	1
24	1	1	1	-1	1	-1	-1	-1
25	-1	-1	-1	1	1	-1	-1	-1
26	1	-1	-1	1	1	-1	1	1
27	-1	1	-1	1	1	-1	1	1
28	1	1	-1	1	1	-1	-1	-1
29	-1	-1	1	1	1	-1	1	-1
30	1	-1	1	1	1	-1	-1	1
31	-1	1	1	1	1	-1	-1	1
32	1	1	1	1	1	-1	1	-1

Design								
Run	A	B	C	D	E	F	G	H
33	-1	-1	-1	-1	-1	1	1	-1
34	1	-1	-1	-1	-1	1	-1	1
35	-1	1	-1	-1	-1	1	-1	1
36	1	1	-1	-1	-1	1	1	-1
37	-1	-1	1	-1	-1	1	-1	-1
38	1	-1	1	-1	-1	1	1	1
39	-1	1	1	-1	-1	1	1	1
40	1	1	1	-1	-1	1	-1	-1
41	-1	-1	-1	1	-1	1	-1	-1
42	1	-1	-1	1	-1	1	1	1
43	-1	1	-1	1	-1	1	1	1
44	1	1	-1	1	-1	1	-1	-1
45	-1	-1	1	1	-1	1	1	-1
46	1	-1	1	1	-1	1	-1	1
47	-1	1	1	1	-1	1	-1	1
48	1	1	1	1	-1	1	1	-1
49	-1	-1	-1	-1	1	1	1	1
50	1	-1	-1	-1	1	1	-1	-1
51	-1	1	-1	-1	1	1	-1	-1
52	1	1	-1	-1	1	1	1	1
53	-1	-1	1	-1	1	1	-1	1
54	1	-1	1	-1	1	1	1	-1
55	-1	1	1	-1	1	1	1	-1
56	1	1	1	-1	1	1	-1	1
57	-1	-1	-1	1	1	1	-1	1
58	1	-1	-1	1	1	1	1	-1
59	-1	1	-1	1	1	1	1	-1
60	1	1	-1	1	1	1	-1	1
61	-1	-1	1	1	1	1	1	1
62	1	-1	1	1	1	1	-1	-1
63	-1	1	1	1	1	1	-1	-1
64	1	1	1	1	1	1	1	1

8 Coefficients, 2 levels, 1/8 Fractional Factorial Design

GENERAL DESIGN INFORMATION

32 runs, 8 factors,
Resolution IV

Design generating information:

Generators

F=ABC G=ABD H=ACDE

WARNING

CONFOUNDING

AB=CF=DG AC=BF AD=BG AF=BC AG=BD CD=FG CG=DF

Design								
Run	A	B	C	D	E	F	G	H
1	-1	-1	-1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	1	1	-1
3	-1	1	-1	-1	-1	1	1	1
4	1	1	-1	-1	-1	-1	-1	-1
5	-1	-1	1	-1	-1	1	-1	-1
6	1	-1	1	-1	-1	-1	1	1
7	-1	1	1	-1	-1	-1	1	-1
8	1	1	1	-1	-1	1	-1	1
9	-1	-1	-1	1	-1	-1	1	-1
10	1	-1	-1	1	-1	1	-1	1
11	-1	1	-1	1	-1	1	-1	-1
12	1	1	-1	1	-1	-1	1	1
13	-1	-1	1	1	-1	1	1	1
14	1	-1	1	1	-1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1	1
16	1	1	1	1	-1	1	1	-1
17	-1	-1	-1	-1	1	-1	-1	-1
18	1	-1	-1	-1	1	1	1	1
19	-1	1	-1	-1	1	1	1	-1
20	1	1	-1	-1	1	-1	-1	1
21	-1	-1	1	-1	1	1	-1	1
22	1	-1	1	-1	1	-1	1	-1
23	-1	1	1	-1	1	-1	1	1
24	1	1	1	-1	1	1	-1	-1
25	-1	-1	-1	1	1	-1	1	1
26	1	-1	-1	1	1	1	-1	-1
27	-1	1	-1	1	1	1	-1	1
28	1	1	-1	1	1	-1	1	-1
29	-1	-1	1	1	1	1	1	-1
30	1	-1	1	1	1	-1	-1	1
31	-1	1	1	1	1	-1	-1	-1
32	1	1	1	1	1	1	1	1

9 Coefficients, 2 levels, 1/2 Fractional Factorial Design

GENERAL DESIGN INFORMATION

256 runs, 9 factors,

Resolution IX

Design generating information:

Generators

J=ABCDEFGH

Design									
Run	A	B	C	D	E	F	G	H	I
1	-1	-1	-1	-1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	-1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	-1	-1	-1
4	1	1	-1	-1	-1	-1	-1	-1	1
5	-1	-1	1	-1	-1	-1	-1	-1	-1
6	1	-1	1	-1	-1	-1	-1	-1	1
7	-1	1	1	-1	-1	-1	-1	-1	1
8	1	1	1	-1	-1	-1	-1	-1	-1
9	-1	-1	-1	1	-1	-1	-1	-1	-1
10	1	-1	-1	1	-1	-1	-1	-1	1
11	-1	1	-1	1	-1	-1	-1	-1	1
12	1	1	-1	1	-1	-1	-1	-1	-1
13	-1	-1	1	1	-1	-1	-1	-1	1
14	1	-1	1	1	-1	-1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1	-1	-1
16	1	1	1	1	-1	-1	-1	-1	1
17	-1	-1	-1	-1	1	-1	-1	-1	-1
18	1	-1	-1	-1	1	-1	-1	-1	1
19	-1	1	-1	-1	1	-1	-1	-1	1
20	1	1	-1	-1	1	-1	-1	-1	-1
21	-1	-1	1	-1	1	-1	-1	-1	1
22	1	-1	1	-1	1	-1	-1	-1	-1
23	-1	1	1	-1	1	-1	-1	-1	-1
24	1	1	1	-1	1	-1	-1	-1	1
25	-1	-1	-1	1	1	-1	-1	-1	1
26	1	-1	-1	1	1	-1	-1	-1	-1
27	-1	1	-1	1	1	-1	-1	-1	-1
28	1	1	-1	1	1	-1	-1	-1	1
29	-1	-1	1	1	1	-1	-1	-1	-1
30	1	-1	1	1	1	-1	-1	-1	1
31	-1	1	1	1	1	-1	-1	-1	1
32	1	1	1	1	1	-1	-1	-1	-1
33	-1	-1	-1	-1	-1	1	-1	-1	-1
34	1	-1	-1	-1	-1	1	-1	-1	1
35	-1	1	-1	-1	-1	1	-1	-1	1
36	1	1	-1	-1	-1	1	-1	-1	-1
37	-1	-1	1	-1	-1	1	-1	-1	1
38	1	-1	1	-1	-1	1	-1	-1	-1
39	-1	1	1	-1	-1	1	-1	-1	-1
40	1	1	1	-1	-1	1	-1	-1	1

Design									
Run	A	B	C	D	E	F	G	H	I
41	-1	-1	-1	1	-1	1	-1	-1	1
42	1	-1	-1	1	-1	1	-1	-1	-1
43	-1	1	-1	1	-1	1	-1	-1	-1
44	1	1	-1	1	-1	1	-1	-1	1
45	-1	-1	1	1	-1	1	-1	-1	-1
46	1	-1	1	1	-1	1	-1	-1	1
47	-1	1	1	1	-1	1	-1	-1	1
48	1	1	1	1	-1	1	-1	-1	-1
49	-1	-1	-1	-1	1	1	-1	-1	1
50	1	-1	-1	-1	1	1	-1	-1	-1
51	-1	1	-1	-1	1	1	-1	-1	-1
52	1	1	-1	-1	1	1	-1	-1	1
53	-1	-1	1	-1	1	1	-1	-1	-1
54	1	-1	1	-1	1	1	-1	-1	1
55	-1	1	1	-1	1	1	-1	-1	1
56	1	1	1	-1	1	1	-1	-1	-1
57	-1	-1	-1	1	1	1	-1	-1	-1
58	1	-1	-1	1	1	1	-1	-1	1
59	-1	1	-1	1	1	1	-1	-1	1
60	1	1	-1	1	1	1	-1	-1	-1
61	-1	-1	1	1	1	1	-1	-1	1
62	1	-1	1	1	1	1	-1	-1	-1
63	-1	1	1	1	1	1	-1	-1	-1
64	1	1	1	1	1	1	-1	-1	1
65	-1	-1	-1	-1	-1	-1	1	-1	-1
66	1	-1	-1	-1	-1	-1	1	-1	1
67	-1	1	-1	-1	-1	-1	1	-1	1
68	1	1	-1	-1	-1	-1	1	-1	-1
69	-1	-1	1	-1	-1	-1	1	-1	1
70	1	-1	1	-1	-1	-1	1	-1	-1
71	-1	1	1	-1	-1	-1	1	-1	-1
72	1	1	1	-1	-1	-1	1	-1	1
73	-1	-1	-1	1	-1	-1	1	-1	1
74	1	-1	-1	1	-1	-1	1	-1	-1
75	-1	1	-1	1	-1	-1	1	-1	-1
76	1	1	-1	1	-1	-1	1	-1	1
77	-1	-1	1	1	-1	-1	1	-1	-1
78	1	-1	1	1	-1	-1	1	-1	1
79	-1	1	1	1	-1	-1	1	-1	1
80	1	1	1	1	-1	-1	1	-1	-1
81	-1	-1	-1	-1	1	-1	1	-1	1
82	1	-1	-1	-1	1	-1	1	-1	-1
83	-1	1	-1	-1	1	-1	1	-1	-1
84	1	1	-1	-1	1	-1	1	-1	1
85	-1	-1	1	-1	1	-1	1	-1	-1
86	1	-1	1	-1	1	-1	1	-1	1
87	-1	1	1	-1	1	-1	1	-1	1
88	1	1	1	-1	1	-1	1	-1	-1
89	-1	-1	-1	1	1	-1	1	-1	-1
90	1	-1	-1	1	1	-1	1	-1	1

Design									
Run	A	B	C	D	E	F	G	H	I
91	-1	1	-1	1	1	-1	1	-1	1
92	1	1	-1	1	1	-1	1	-1	-1
93	-1	-1	1	1	1	-1	1	-1	1
94	1	-1	1	1	1	-1	1	-1	-1
95	-1	1	1	1	1	-1	1	-1	-1
96	1	1	1	1	1	-1	1	-1	1
97	-1	-1	-1	-1	-1	1	1	-1	1
98	1	-1	-1	-1	-1	1	1	-1	-1
99	-1	1	-1	-1	-1	1	1	-1	-1
100	1	1	-1	-1	-1	1	1	-1	1
101	-1	-1	1	-1	-1	1	1	-1	-1
102	1	-1	1	-1	-1	1	1	-1	1
103	-1	1	1	-1	-1	1	1	-1	1
104	1	1	1	-1	-1	1	1	-1	-1
105	-1	-1	-1	1	-1	1	1	-1	-1
106	1	-1	-1	1	-1	1	1	-1	1
107	-1	1	-1	1	-1	1	1	-1	1
108	1	1	-1	1	-1	1	1	-1	-1
109	-1	-1	1	1	-1	1	1	-1	1
110	1	-1	1	1	-1	1	1	-1	-1
111	-1	1	1	1	-1	1	1	-1	-1
112	1	1	1	1	-1	1	1	-1	1
113	-1	-1	-1	-1	1	1	1	-1	-1
114	1	-1	-1	-1	1	1	1	-1	1
115	-1	1	-1	-1	1	1	1	-1	1
116	1	1	-1	-1	1	1	1	-1	-1
117	-1	-1	1	-1	1	1	1	-1	1
118	1	-1	1	-1	1	1	1	-1	-1
119	-1	1	1	-1	1	1	1	-1	-1
120	1	1	1	-1	1	1	1	-1	1
121	-1	-1	-1	1	1	1	1	-1	1
122	1	-1	-1	1	1	1	1	-1	-1
123	-1	1	-1	1	1	1	1	-1	-1
124	1	1	-1	1	1	1	1	-1	1
125	-1	-1	1	1	1	1	1	-1	-1
126	1	-1	1	1	1	1	1	-1	1
127	-1	1	1	1	1	1	1	-1	1
128	1	1	1	1	1	1	1	-1	-1
129	-1	-1	-1	-1	-1	-1	-1	1	-1
130	1	-1	-1	-1	-1	-1	-1	1	1
131	-1	1	-1	-1	-1	-1	-1	1	1
132	1	1	-1	-1	-1	-1	-1	1	-1
133	-1	-1	1	-1	-1	-1	-1	1	1
134	1	-1	1	-1	-1	-1	-1	1	-1
135	-1	1	1	-1	-1	-1	-1	1	-1
136	1	1	1	-1	-1	-1	-1	1	1
137	-1	-1	-1	1	-1	-1	-1	1	1
138	1	-1	-1	1	-1	-1	-1	1	-1
139	-1	1	-1	1	-1	-1	-1	1	-1
140	1	1	-1	1	-1	-1	-1	1	1

Design									
Run	A	B	C	D	E	F	G	H	I
141	-1	-1	1	1	-1	-1	-1	1	-1
142	1	-1	1	1	-1	-1	-1	1	1
143	-1	1	1	1	-1	-1	-1	1	1
144	1	1	1	1	-1	-1	-1	1	-1
145	-1	-1	-1	-1	1	-1	-1	1	1
146	1	-1	-1	-1	1	-1	-1	1	-1
147	-1	1	-1	-1	1	-1	-1	1	-1
148	1	1	-1	-1	1	-1	-1	1	1
149	-1	-1	1	-1	1	-1	-1	1	-1
150	1	-1	1	-1	1	-1	-1	1	1
151	-1	1	1	-1	1	-1	-1	1	1
152	1	1	1	-1	1	-1	-1	1	-1
153	-1	-1	-1	1	1	-1	-1	1	-1
154	1	-1	-1	1	1	-1	-1	1	1
155	-1	1	-1	1	1	-1	-1	1	1
156	1	1	-1	1	1	-1	-1	1	-1
157	-1	-1	1	1	1	-1	-1	1	1
158	1	-1	1	1	1	-1	-1	1	-1
159	-1	1	1	1	1	-1	-1	1	-1
160	1	1	1	1	1	-1	-1	1	1
161	-1	-1	-1	-1	-1	1	-1	1	1
162	1	-1	-1	-1	-1	1	-1	1	-1
163	-1	1	-1	-1	-1	1	-1	1	-1
164	1	1	-1	-1	-1	1	-1	1	1
165	-1	-1	1	-1	-1	1	-1	1	-1
166	1	-1	1	-1	-1	1	-1	1	1
167	-1	1	1	-1	-1	1	-1	1	1
168	1	1	1	-1	-1	1	-1	1	-1
169	-1	-1	-1	1	-1	1	-1	1	-1
170	1	-1	-1	1	-1	1	-1	1	1
171	-1	1	-1	1	-1	1	-1	1	1
172	1	1	-1	1	-1	1	-1	1	-1
173	-1	-1	1	1	-1	1	-1	1	1
174	1	-1	1	1	-1	1	-1	1	-1
175	-1	1	1	1	-1	1	-1	1	-1
176	1	1	1	1	-1	1	-1	1	1
177	-1	-1	-1	-1	1	1	-1	1	-1
178	1	-1	-1	-1	1	1	-1	1	1
179	-1	1	-1	-1	1	1	-1	1	1
180	1	1	-1	-1	1	1	-1	1	-1
181	-1	-1	1	-1	1	1	-1	1	1
182	1	-1	1	-1	1	1	-1	1	-1
183	-1	1	1	-1	1	1	-1	1	-1
184	1	1	1	-1	1	1	-1	1	1
185	-1	-1	-1	1	1	1	-1	1	1
186	1	-1	-1	1	1	1	-1	1	-1
187	-1	1	-1	1	1	1	-1	1	-1
188	1	1	-1	1	1	1	-1	1	1
189	-1	-1	1	1	1	1	-1	1	-1
190	1	-1	1	1	1	1	-1	1	1

Design									
Run	A	B	C	D	E	F	G	H	I
191	-1	1	1	1	1	1	-1	1	1
192	1	1	1	1	1	1	-1	1	-1
193	-1	-1	-1	-1	-1	-1	1	1	1
194	1	-1	-1	-1	-1	-1	1	1	-1
195	-1	1	-1	-1	-1	-1	1	1	-1
196	1	1	-1	-1	-1	-1	1	1	1
197	-1	-1	1	-1	-1	-1	1	1	-1
198	1	-1	1	-1	-1	-1	1	1	1
199	-1	1	1	-1	-1	-1	1	1	1
200	1	1	1	-1	-1	-1	1	1	-1
201	-1	-1	-1	1	-1	-1	1	1	-1
202	1	-1	-1	1	-1	-1	1	1	1
203	-1	1	-1	1	-1	-1	1	1	1
204	1	1	-1	1	-1	-1	1	1	-1
205	-1	-1	1	1	-1	-1	1	1	1
206	1	-1	1	1	-1	-1	1	1	-1
207	-1	1	1	1	-1	-1	1	1	-1
208	1	1	1	1	-1	-1	1	1	1
209	-1	-1	-1	-1	1	-1	1	1	-1
210	1	-1	-1	-1	1	-1	1	1	1
211	-1	1	-1	-1	1	-1	1	1	1
212	1	1	-1	-1	1	-1	1	1	-1
213	-1	-1	1	-1	1	-1	1	1	1
214	1	-1	1	-1	1	-1	1	1	-1
215	-1	1	1	-1	1	-1	1	1	-1
216	1	1	1	-1	1	-1	1	1	1
217	-1	-1	-1	1	1	-1	1	1	1
218	1	-1	-1	1	1	-1	1	1	-1
219	-1	1	-1	1	1	-1	1	1	-1
220	1	1	-1	1	1	-1	1	1	1
221	-1	-1	1	1	1	-1	1	1	-1
222	1	-1	1	1	1	-1	1	1	1
223	-1	1	1	1	1	-1	1	1	1
224	1	1	1	1	1	-1	1	1	-1
225	-1	-1	-1	-1	-1	1	1	1	-1
226	1	-1	-1	-1	-1	1	1	1	1
227	-1	1	-1	-1	-1	1	1	1	1
228	1	1	-1	-1	-1	1	1	1	-1
229	-1	-1	1	-1	-1	1	1	1	1
230	1	-1	1	-1	-1	1	1	1	-1
231	-1	1	1	-1	-1	1	1	1	-1
232	1	1	1	-1	-1	1	1	1	1
233	-1	-1	-1	1	-1	1	1	1	1
234	1	-1	-1	1	-1	1	1	1	-1
235	-1	1	-1	1	-1	1	1	1	-1
236	1	1	-1	1	-1	1	1	1	1
237	-1	-1	1	1	-1	1	1	1	-1
238	1	-1	1	1	-1	1	1	1	1
239	-1	1	1	1	-1	1	1	1	1
240	1	1	1	1	-1	1	1	1	-1

Design									
Run	A	B	C	D	E	F	G	H	I
241	-1	-1	-1	-1	1	1	1	1	1
242	1	-1	-1	-1	1	1	1	1	-1
243	-1	1	-1	-1	1	1	1	1	-1
244	1	1	-1	-1	1	1	1	1	1
245	-1	-1	1	-1	1	1	1	1	-1
246	1	-1	1	-1	1	1	1	1	1
247	-1	1	1	-1	1	1	1	1	1
248	1	1	1	-1	1	1	1	1	-1
249	-1	-1	-1	1	1	1	1	1	-1
250	1	-1	-1	1	1	1	1	1	1
251	-1	1	-1	1	1	1	1	1	1
252	1	1	-1	1	1	1	1	1	-1
253	-1	-1	1	1	1	1	1	1	1
254	1	-1	1	1	1	1	1	1	-1
255	-1	1	1	1	1	1	1	1	-1
256	1	1	1	1	1	1	1	1	1

9 Coefficients, 2 levels, 1/4 Fractional Factorial Design

GENERAL DESIGN INFORMATION

128 runs, 9 factors,
Resolution VI

Design generating information:

Generators

H=ABCDE J=ABCFG

Design									
Run	A	B	C	D	E	F	G	H	I
1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	-1	-1	-1	1	1
3	-1	1	-1	-1	-1	-1	-1	1	1
4	1	1	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	1	-1	-1	-1	-1	1	1
6	1	-1	1	-1	-1	-1	-1	-1	-1
7	-1	1	1	-1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	-1	1	1
9	-1	-1	-1	1	-1	-1	-1	1	-1
10	1	-1	-1	1	-1	-1	-1	-1	1
11	-1	1	-1	1	-1	-1	-1	-1	1
12	1	1	-1	1	-1	-1	-1	1	-1
13	-1	-1	1	1	-1	-1	-1	-1	1
14	1	-1	1	1	-1	-1	-1	1	-1
15	-1	1	1	1	-1	-1	-1	1	-1
16	1	1	1	1	-1	-1	-1	-1	1
17	-1	-1	-1	-1	1	-1	-1	1	-1
18	1	-1	-1	-1	1	-1	-1	-1	1
19	-1	1	-1	-1	1	-1	-1	-1	1
20	1	1	-1	-1	1	-1	-1	1	-1
21	-1	-1	1	-1	1	-1	-1	-1	1
22	1	-1	1	-1	1	-1	-1	1	-1
23	-1	1	1	-1	1	-1	-1	1	-1
24	1	1	1	-1	1	-1	-1	-1	1
25	-1	-1	-1	1	1	-1	-1	-1	-1
26	1	-1	-1	1	1	-1	-1	1	1
27	-1	1	-1	1	1	-1	-1	1	1
28	1	1	-1	1	1	-1	-1	-1	-1
29	-1	-1	1	1	1	-1	-1	1	1
30	1	-1	1	1	1	-1	-1	-1	-1
31	-1	1	1	1	1	-1	-1	-1	-1
32	1	1	1	1	1	-1	-1	1	1
33	-1	-1	-1	-1	-1	1	-1	-1	1
34	1	-1	-1	-1	-1	1	-1	1	-1
35	-1	1	-1	-1	-1	1	-1	1	-1
36	1	1	-1	-1	-1	1	-1	-1	1
37	-1	-1	1	-1	-1	1	-1	1	-1
38	1	-1	1	-1	-1	1	-1	-1	1
39	-1	1	1	-1	-1	1	-1	-1	1
40	1	1	1	-1	-1	1	-1	1	-1

Design									
Run	A	B	C	D	E	F	G	H	I
41	-1	-1	-1	1	-1	1	-1	1	1
42	1	-1	-1	1	-1	1	-1	-1	-1
43	-1	1	-1	1	-1	1	-1	-1	-1
44	1	1	-1	1	-1	1	-1	1	1
45	-1	-1	1	1	-1	1	-1	-1	-1
46	1	-1	1	1	-1	1	-1	1	1
47	-1	1	1	1	-1	1	-1	1	1
48	1	1	1	1	-1	1	-1	-1	-1
49	-1	-1	-1	-1	1	1	-1	1	1
50	1	-1	-1	-1	1	1	-1	-1	-1
51	-1	1	-1	-1	1	1	-1	-1	-1
52	1	1	-1	-1	1	1	-1	1	1
53	-1	-1	1	-1	1	1	-1	-1	-1
54	1	-1	1	-1	1	1	-1	1	1
55	-1	1	1	-1	1	1	-1	1	1
56	1	1	1	-1	1	1	-1	-1	-1
57	-1	-1	-1	1	1	1	-1	-1	1
58	1	-1	-1	1	1	1	-1	1	-1
59	-1	1	-1	1	1	1	-1	1	-1
60	1	1	-1	1	1	1	-1	-1	1
61	-1	-1	1	1	1	1	-1	1	-1
62	1	-1	1	1	1	1	-1	-1	1
63	-1	1	1	1	1	1	-1	-1	1
64	1	1	1	1	1	1	-1	1	-1
65	-1	-1	-1	-1	-1	-1	1	-1	1
66	1	-1	-1	-1	-1	-1	1	1	-1
67	-1	1	-1	-1	-1	-1	1	1	-1
68	1	1	-1	-1	-1	-1	1	-1	1
69	-1	-1	1	-1	-1	-1	1	1	-1
70	1	-1	1	-1	-1	-1	1	-1	1
71	-1	1	1	-1	-1	-1	1	-1	1
72	1	1	1	-1	-1	-1	1	1	-1
73	-1	-1	-1	1	-1	-1	1	1	1
74	1	-1	-1	1	-1	-1	1	-1	-1
75	-1	1	-1	1	-1	-1	1	-1	-1
76	1	1	-1	1	-1	-1	1	1	1
77	-1	-1	1	1	-1	-1	1	-1	-1
78	1	-1	1	1	-1	-1	1	1	1
79	-1	1	1	1	-1	-1	1	1	1
80	1	1	1	1	-1	-1	1	-1	-1
81	-1	-1	-1	-1	1	-1	1	1	1
82	1	-1	-1	-1	1	-1	1	-1	-1
83	-1	1	-1	-1	1	-1	1	-1	-1
84	1	1	-1	-1	1	-1	1	1	1
85	-1	-1	1	-1	1	-1	1	-1	-1
86	1	-1	1	-1	1	-1	1	1	1
87	-1	1	1	-1	1	-1	1	1	1
88	1	1	1	-1	1	-1	1	-1	-1
89	-1	-1	-1	1	1	-1	1	-1	1
90	1	-1	-1	1	1	-1	1	1	-1

Design									
Run	A	B	C	D	E	F	G	H	I
91	-1	1	-1	1	1	-1	1	1	-1
92	1	1	-1	1	1	-1	1	-1	1
93	-1	-1	1	1	1	-1	1	1	-1
94	1	-1	1	1	1	-1	1	-1	1
95	-1	1	1	1	1	-1	1	-1	1
96	1	1	1	1	1	-1	1	1	-1
97	-1	-1	-1	-1	-1	1	1	-1	-1
98	1	-1	-1	-1	-1	1	1	1	1
99	-1	1	-1	-1	-1	1	1	1	1
100	1	1	-1	-1	-1	1	1	-1	-1
101	-1	-1	1	-1	-1	1	1	1	1
102	1	-1	1	-1	-1	1	1	-1	-1
103	-1	1	1	-1	-1	1	1	-1	-1
104	1	1	1	-1	-1	1	1	1	1
105	-1	-1	-1	1	-1	1	1	1	-1
106	1	-1	-1	1	-1	1	1	-1	1
107	-1	1	-1	1	-1	1	1	-1	1
108	1	1	-1	1	-1	1	1	1	-1
109	-1	-1	1	1	-1	1	1	-1	1
110	1	-1	1	1	-1	1	1	1	-1
111	-1	1	1	1	-1	1	1	1	-1
112	1	1	1	1	-1	1	1	-1	1
113	-1	-1	-1	-1	1	1	1	1	-1
114	1	-1	-1	-1	1	1	1	-1	1
115	-1	1	-1	-1	1	1	1	-1	1
116	1	1	-1	-1	1	1	1	1	-1
117	-1	-1	1	-1	1	1	1	-1	1
118	1	-1	1	-1	1	1	1	1	-1
119	-1	1	1	-1	1	1	1	1	-1
120	1	1	1	-1	1	1	1	-1	1
121	-1	-1	-1	1	1	1	1	-1	-1
122	1	-1	-1	1	1	1	1	1	1
123	-1	1	-1	1	1	1	1	1	1
124	1	1	-1	1	1	1	1	-1	-1
125	-1	-1	1	1	1	1	1	1	1
126	1	-1	1	1	1	1	1	-1	-1
127	-1	1	1	1	1	1	1	-1	-1
128	1	1	1	1	1	1	1	1	1

9 Coefficients, 2 levels, 1/8 Fractional Factorial Design

GENERAL DESIGN INFORMATION

64 runs, 9 factors,
Resolution IV

Design generating information:

Generators

G=ABC H=ABDE J=ACDF

WARNING

CONFOUNDING

AB=CG AC=BG AG=BC

Design									
Run	A	B	C	D	E	F	G	H	I
1	-1	-1	-1	-1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1	-1	1	-1	-1
3	-1	1	-1	-1	-1	-1	1	-1	1
4	1	1	-1	-1	-1	-1	-1	1	-1
5	-1	-1	1	-1	-1	-1	1	1	-1
6	1	-1	1	-1	-1	-1	-1	-1	1
7	-1	1	1	-1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	1	1	1
9	-1	-1	-1	1	-1	-1	-1	-1	-1
10	1	-1	-1	1	-1	-1	1	1	1
11	-1	1	-1	1	-1	-1	1	1	-1
12	1	1	-1	1	-1	-1	-1	-1	1
13	-1	-1	1	1	-1	-1	1	-1	1
14	1	-1	1	1	-1	-1	-1	1	-1
15	-1	1	1	1	-1	-1	-1	1	1
16	1	1	1	1	-1	-1	1	-1	-1
17	-1	-1	-1	-1	1	-1	-1	-1	1
18	1	-1	-1	-1	1	-1	1	1	-1
19	-1	1	-1	-1	1	-1	1	1	1
20	1	1	-1	-1	1	-1	-1	-1	-1
21	-1	-1	1	-1	1	-1	1	-1	-1
22	1	-1	1	-1	1	-1	-1	1	1
23	-1	1	1	-1	1	-1	-1	1	-1
24	1	1	1	-1	1	-1	1	-1	1
25	-1	-1	-1	1	1	-1	-1	1	-1
26	1	-1	-1	1	1	-1	1	-1	1
27	-1	1	-1	1	1	-1	1	-1	-1
28	1	1	-1	1	1	-1	-1	1	1
29	-1	-1	1	1	1	-1	1	1	1
30	1	-1	1	1	1	-1	-1	-1	-1
31	-1	1	1	1	1	-1	-1	-1	1
32	1	1	1	1	1	-1	1	1	-1

Design									
Run	A	B	C	D	E	F	G	H	I
33	-1	-1	-1	-1	-1	1	-1	1	-1
34	1	-1	-1	-1	-1	1	1	-1	1
35	-1	1	-1	-1	-1	1	1	-1	-1
36	1	1	-1	-1	-1	1	-1	1	1
37	-1	-1	1	-1	-1	1	1	1	1
38	1	-1	1	-1	-1	1	-1	-1	-1
39	-1	1	1	-1	-1	1	-1	-1	1
40	1	1	1	-1	-1	1	1	1	-1
41	-1	-1	-1	1	-1	1	-1	-1	1
42	1	-1	-1	1	-1	1	1	1	-1
43	-1	1	-1	1	-1	1	1	1	1
44	1	1	-1	1	-1	1	-1	-1	-1
45	-1	-1	1	1	-1	1	1	-1	-1
46	1	-1	1	1	-1	1	-1	1	1
47	-1	1	1	1	-1	1	-1	1	-1
48	1	1	1	1	-1	1	1	-1	1
49	-1	-1	-1	-1	1	1	-1	-1	-1
50	1	-1	-1	-1	1	1	1	1	1
51	-1	1	-1	-1	1	1	1	1	-1
52	1	1	-1	-1	1	1	-1	-1	1
53	-1	-1	1	-1	1	1	1	-1	1
54	1	-1	1	-1	1	1	-1	1	-1
55	-1	1	1	-1	1	1	-1	1	1
56	1	1	1	-1	1	1	1	-1	-1
57	-1	-1	-1	1	1	1	-1	1	1
58	1	-1	-1	1	1	1	1	-1	-1
59	-1	1	-1	1	1	1	1	-1	1
60	1	1	-1	1	1	1	-1	1	-1
61	-1	-1	1	1	1	1	1	1	-1
62	1	-1	1	1	1	1	-1	-1	1
63	-1	1	1	1	1	1	-1	-1	-1
64	1	1	1	1	1	1	1	1	1

10 Coefficients, 2 levels, 1/4 Fractional Factorial Design

GENERAL DESIGN INFORMATION

256 runs, 10 factors,
Resolution VI

Design generating information:

Generators

J=ABCDEF K=ABCGH

Design										
Run	A	B	C	D	E	F	G	H	I	J
1	-1	-1	-1	-1	-1	-1	-1	-1	1	-1
2	1	-1	-1	-1	-1	-1	-1	-1	-1	1
3	-1	1	-1	-1	-1	-1	-1	-1	-1	1
4	1	1	-1	-1	-1	-1	-1	-1	1	-1
5	-1	-1	1	-1	-1	-1	-1	-1	-1	1
6	1	-1	1	-1	-1	-1	-1	-1	1	-1
7	-1	1	1	-1	-1	-1	-1	-1	1	-1
8	1	1	1	-1	-1	-1	-1	-1	-1	1
9	-1	-1	-1	1	-1	-1	-1	-1	-1	-1
10	1	-1	-1	1	-1	-1	-1	-1	1	1
11	-1	1	-1	1	-1	-1	-1	-1	1	1
12	1	1	-1	1	-1	-1	-1	-1	-1	-1
13	-1	-1	1	1	-1	-1	-1	-1	1	1
14	1	-1	1	1	-1	-1	-1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1	-1	-1	-1
16	1	1	1	1	-1	-1	-1	-1	1	1
17	-1	-1	-1	-1	1	-1	-1	-1	-1	-1
18	1	-1	-1	-1	1	-1	-1	-1	1	1
19	-1	1	-1	-1	1	-1	-1	-1	1	1
20	1	1	-1	-1	1	-1	-1	-1	-1	-1
21	-1	-1	1	-1	1	-1	-1	-1	1	1
22	1	-1	1	-1	1	-1	-1	-1	-1	-1
23	-1	1	1	-1	1	-1	-1	-1	-1	-1
24	1	1	1	-1	1	-1	-1	-1	1	1
25	-1	-1	-1	1	1	-1	-1	-1	1	-1
26	1	-1	-1	1	1	-1	-1	-1	-1	1
27	-1	1	-1	1	1	-1	-1	-1	-1	1
28	1	1	-1	1	1	-1	-1	-1	1	-1
29	-1	-1	1	1	1	-1	-1	-1	-1	1
30	1	-1	1	1	1	-1	-1	-1	1	-1
31	-1	1	1	1	1	-1	-1	-1	1	-1
32	1	1	1	1	1	-1	-1	-1	-1	1
33	-1	-1	-1	-1	-1	1	-1	-1	-1	-1
34	1	-1	-1	-1	-1	1	-1	-1	1	1
35	-1	1	-1	-1	-1	1	-1	-1	1	1
36	1	1	-1	-1	-1	1	-1	-1	-1	-1
37	-1	-1	1	-1	-1	1	-1	-1	1	1
38	1	-1	1	-1	-1	1	-1	-1	-1	-1
39	-1	1	1	-1	-1	1	-1	-1	-1	-1
40	1	1	1	-1	-1	1	-1	-1	1	1

Design										
Run	A	B	C	D	E	F	G	H	I	J
41	-1	-1	-1	1	-1	1	-1	-1	1	-1
42	1	-1	-1	1	-1	1	-1	-1	-1	1
43	-1	1	-1	1	-1	1	-1	-1	-1	1
44	1	1	-1	1	-1	1	-1	-1	1	-1
45	-1	-1	1	1	-1	1	-1	-1	-1	1
46	1	-1	1	1	-1	1	-1	-1	1	-1
47	-1	1	1	1	-1	1	-1	-1	1	-1
48	1	1	1	1	-1	1	-1	-1	-1	1
49	-1	-1	-1	-1	1	1	-1	-1	1	-1
50	1	-1	-1	-1	1	1	-1	-1	-1	1
51	-1	1	-1	-1	1	1	-1	-1	-1	1
52	1	1	-1	-1	1	1	-1	-1	1	-1
53	-1	-1	1	-1	1	1	-1	-1	-1	1
54	1	-1	1	-1	1	1	-1	-1	1	-1
55	-1	1	1	-1	1	1	-1	-1	1	-1
56	1	1	1	-1	1	1	-1	-1	-1	1
57	-1	-1	-1	1	1	1	-1	-1	-1	-1
58	1	-1	-1	1	1	1	-1	-1	1	1
59	-1	1	-1	1	1	1	-1	-1	1	1
60	1	1	-1	1	1	1	-1	-1	-1	-1
61	-1	-1	1	1	1	1	-1	-1	1	1
62	1	-1	1	1	1	1	-1	-1	-1	-1
63	-1	1	1	1	1	1	-1	-1	-1	-1
64	1	1	1	1	1	1	-1	-1	1	1
65	-1	-1	-1	-1	-1	-1	1	-1	1	1
66	1	-1	-1	-1	-1	-1	1	-1	-1	-1
67	-1	1	-1	-1	-1	-1	1	-1	-1	-1
68	1	1	-1	-1	-1	-1	1	-1	1	1
69	-1	-1	1	-1	-1	-1	1	-1	-1	-1
70	1	-1	1	-1	-1	-1	1	-1	1	1
71	-1	1	1	-1	-1	-1	1	-1	1	1
72	1	1	1	-1	-1	-1	1	-1	-1	-1
73	-1	-1	-1	1	-1	-1	1	-1	-1	1
74	1	-1	-1	1	-1	-1	1	-1	1	-1
75	-1	1	-1	1	-1	-1	1	-1	1	-1
76	1	1	-1	1	-1	-1	1	-1	-1	1
77	-1	-1	1	1	-1	-1	1	-1	1	-1
78	1	-1	1	1	-1	-1	1	-1	-1	1
79	-1	1	1	1	-1	-1	1	-1	-1	1
80	1	1	1	1	-1	-1	1	-1	1	-1
81	-1	-1	-1	-1	1	-1	1	-1	-1	1
82	1	-1	-1	-1	1	-1	1	-1	1	-1
83	-1	1	-1	-1	1	-1	1	-1	1	-1
84	1	1	-1	-1	1	-1	1	-1	-1	1
85	-1	-1	1	-1	1	-1	1	-1	1	-1
86	1	-1	1	-1	1	-1	1	-1	-1	1
87	-1	1	1	-1	1	-1	1	-1	-1	1
88	1	1	1	-1	1	-1	1	-1	1	-1
89	-1	-1	-1	1	1	-1	1	-1	1	1
90	1	-1	-1	1	1	-1	1	-1	-1	-1

Design										
Run	A	B	C	D	E	F	G	H	I	J
91	-1	1	-1	1	1	-1	1	-1	-1	-1
92	1	1	-1	1	1	-1	1	-1	1	1
93	-1	-1	1	1	1	-1	1	-1	-1	-1
94	1	-1	1	1	1	-1	1	-1	1	1
95	-1	1	1	1	1	-1	1	-1	1	1
96	1	1	1	1	1	-1	1	-1	-1	-1
97	-1	-1	-1	-1	-1	1	1	-1	-1	1
98	1	-1	-1	-1	-1	1	1	-1	1	-1
99	-1	1	-1	-1	-1	1	1	-1	1	-1
100	1	1	-1	-1	-1	1	1	-1	-1	1
101	-1	-1	1	-1	-1	1	1	-1	1	-1
102	1	-1	1	-1	-1	1	1	-1	-1	1
103	-1	1	1	-1	-1	1	1	-1	-1	1
104	1	1	1	-1	-1	1	1	-1	1	-1
105	-1	-1	-1	1	-1	1	1	-1	1	1
106	1	-1	-1	1	-1	1	1	-1	-1	-1
107	-1	1	-1	1	-1	1	1	-1	-1	-1
108	1	1	-1	1	-1	1	1	-1	1	1
109	-1	-1	1	1	-1	1	1	-1	-1	-1
110	1	-1	1	1	-1	1	1	-1	1	1
111	-1	1	1	1	-1	1	1	-1	1	1
112	1	1	1	1	-1	1	1	-1	-1	-1
113	-1	-1	-1	-1	1	1	1	-1	1	1
114	1	-1	-1	-1	1	1	1	-1	-1	-1
115	-1	1	-1	-1	1	1	1	-1	-1	-1
116	1	1	-1	-1	1	1	1	-1	1	1
117	-1	-1	1	-1	1	1	1	-1	-1	-1
118	1	-1	1	-1	1	1	1	-1	1	1
119	-1	1	1	-1	1	1	1	-1	1	1
120	1	1	1	-1	1	1	1	-1	-1	-1
121	-1	-1	-1	1	1	1	1	-1	-1	1
122	1	-1	-1	1	1	1	1	-1	1	-1
123	-1	1	-1	1	1	1	1	-1	1	-1
124	1	1	-1	1	1	1	1	-1	-1	1
125	-1	-1	1	1	1	1	1	-1	1	-1
126	1	-1	1	1	1	1	1	-1	-1	1
127	-1	1	1	1	1	1	1	-1	-1	1
128	1	1	1	1	1	1	1	-1	1	-1
129	-1	-1	-1	-1	-1	-1	-1	1	1	1
130	1	-1	-1	-1	-1	-1	-1	1	-1	-1
131	-1	1	-1	-1	-1	-1	-1	1	-1	-1
132	1	1	-1	-1	-1	-1	-1	1	1	1
133	-1	-1	1	-1	-1	-1	-1	1	-1	-1
134	1	-1	1	-1	-1	-1	-1	1	1	1
135	-1	1	1	-1	-1	-1	-1	1	1	1
136	1	1	1	-1	-1	-1	-1	1	-1	-1
137	-1	-1	-1	1	-1	-1	-1	1	-1	1
138	1	-1	-1	1	-1	-1	-1	1	1	-1
139	-1	1	-1	1	-1	-1	-1	1	1	-1
140	1	1	-1	1	-1	-1	-1	1	-1	1

Design										
Run	A	B	C	D	E	F	G	H	I	J
141	-1	-1	1	1	-1	-1	-1	1	1	-1
142	1	-1	1	1	-1	-1	-1	1	-1	1
143	-1	1	1	1	-1	-1	-1	1	-1	1
144	1	1	1	1	-1	-1	-1	1	1	-1
145	-1	-1	-1	-1	1	-1	-1	1	-1	1
146	1	-1	-1	-1	1	-1	-1	1	1	-1
147	-1	1	-1	-1	1	-1	-1	1	1	-1
148	1	1	-1	-1	1	-1	-1	1	-1	1
149	-1	-1	1	-1	1	-1	-1	1	1	-1
150	1	-1	1	-1	1	-1	-1	1	-1	1
151	-1	1	1	-1	1	-1	-1	1	-1	1
152	1	1	1	-1	1	-1	-1	1	1	-1
153	-1	-1	-1	1	1	-1	-1	1	1	1
154	1	-1	-1	1	1	-1	-1	1	-1	-1
155	-1	1	-1	1	1	-1	-1	1	-1	-1
156	1	1	-1	1	1	-1	-1	1	1	1
157	-1	-1	1	1	1	-1	-1	1	-1	-1
158	1	-1	1	1	1	-1	-1	1	1	1
159	-1	1	1	1	1	-1	-1	1	1	1
160	1	1	1	1	1	-1	-1	1	-1	-1
161	-1	-1	-1	-1	-1	1	-1	1	-1	1
162	1	-1	-1	-1	-1	1	-1	1	1	-1
163	-1	1	-1	-1	-1	1	-1	1	1	-1
164	1	1	-1	-1	-1	1	-1	1	-1	1
165	-1	-1	1	-1	-1	1	-1	1	1	-1
166	1	-1	1	-1	-1	1	-1	1	-1	1
167	-1	1	1	-1	-1	1	-1	1	-1	1
168	1	1	1	-1	-1	1	-1	1	1	-1
169	-1	-1	-1	1	-1	1	-1	1	1	1
170	1	-1	-1	1	-1	1	-1	1	-1	-1
171	-1	1	-1	1	-1	1	-1	1	-1	-1
172	1	1	-1	1	-1	1	-1	1	1	1
173	-1	-1	1	1	-1	1	-1	1	-1	-1
174	1	-1	1	1	-1	1	-1	1	1	1
175	-1	1	1	1	-1	1	-1	1	1	1
176	1	1	1	1	-1	1	-1	1	-1	-1
177	-1	-1	-1	-1	1	1	-1	1	1	1
178	1	-1	-1	-1	1	1	-1	1	-1	-1
179	-1	1	-1	-1	1	1	-1	1	-1	-1
180	1	1	-1	-1	1	1	-1	1	1	1
181	-1	-1	1	-1	1	1	-1	1	-1	-1
182	1	-1	1	-1	1	1	-1	1	1	1
183	-1	1	1	-1	1	1	-1	1	1	1
184	1	1	1	-1	1	1	-1	1	-1	-1
185	-1	-1	-1	1	1	1	-1	1	-1	1
186	1	-1	-1	1	1	1	-1	1	1	-1
187	-1	1	-1	1	1	1	-1	1	1	-1
188	1	1	-1	1	1	1	-1	1	-1	1
189	-1	-1	1	1	1	1	-1	1	1	-1
190	1	-1	1	1	1	1	-1	1	-1	1

Design										
Run	A	B	C	D	E	F	G	H	I	J
191	-1	1	1	1	1	1	-1	1	-1	1
192	1	1	1	1	1	1	-1	1	1	-1
193	-1	-1	-1	-1	-1	-1	1	1	1	-1
194	1	-1	-1	-1	-1	-1	1	1	-1	1
195	-1	1	-1	-1	-1	-1	1	1	-1	1
196	1	1	-1	-1	-1	-1	1	1	1	-1
197	-1	-1	1	-1	-1	-1	1	1	-1	1
198	1	-1	1	-1	-1	-1	1	1	1	-1
199	-1	1	1	-1	-1	-1	1	1	1	-1
200	1	1	1	-1	-1	-1	1	1	-1	1
201	-1	-1	-1	1	-1	-1	1	1	-1	-1
202	1	-1	-1	1	-1	-1	1	1	1	1
203	-1	1	-1	1	-1	-1	1	1	1	1
204	1	1	-1	1	-1	-1	1	1	-1	-1
205	-1	-1	1	1	-1	-1	1	1	1	1
206	1	-1	1	1	-1	-1	1	1	-1	-1
207	-1	1	1	1	-1	-1	1	1	-1	-1
208	1	1	1	1	-1	-1	1	1	1	1
209	-1	-1	-1	-1	1	-1	1	1	-1	-1
210	1	-1	-1	-1	1	-1	1	1	1	1
211	-1	1	-1	-1	1	-1	1	1	1	1
212	1	1	-1	-1	1	-1	1	1	-1	-1
213	-1	-1	1	-1	1	-1	1	1	1	1
214	1	-1	1	-1	1	-1	1	1	-1	-1
215	-1	1	1	-1	1	-1	1	1	-1	-1
216	1	1	1	-1	1	-1	1	1	1	1
217	-1	-1	-1	1	1	-1	1	1	1	-1
218	1	-1	-1	1	1	-1	1	1	-1	1
219	-1	1	-1	1	1	-1	1	1	-1	1
220	1	1	-1	1	1	-1	1	1	1	-1
221	-1	-1	1	1	1	-1	1	1	-1	1
222	1	-1	1	1	1	-1	1	1	1	-1
223	-1	1	1	1	1	-1	1	1	1	-1
224	1	1	1	1	1	-1	1	1	-1	1
225	-1	-1	-1	-1	-1	1	1	1	-1	-1
226	1	-1	-1	-1	-1	1	1	1	1	1
227	-1	1	-1	-1	-1	1	1	1	1	1
228	1	1	-1	-1	-1	1	1	1	-1	-1
229	-1	-1	1	-1	-1	1	1	1	1	1
230	1	-1	1	-1	-1	1	1	1	-1	-1
231	-1	1	1	-1	-1	1	1	1	-1	-1
232	1	1	1	-1	-1	1	1	1	1	1
233	-1	-1	-1	1	-1	1	1	1	1	-1
234	1	-1	-1	1	-1	1	1	1	-1	1
235	-1	1	-1	1	-1	1	1	1	-1	1
236	1	1	-1	1	-1	1	1	1	1	-1
237	-1	-1	1	1	-1	1	1	1	-1	1
238	1	-1	1	1	-1	1	1	1	1	-1
239	-1	1	1	1	-1	1	1	1	1	-1
240	1	1	1	1	-1	1	1	1	-1	1

Design										
Run	A	B	C	D	E	F	G	H	I	J
241	-1	-1	-1	-1	1	1	1	1	1	-1
242	1	-1	-1	-1	1	1	1	1	-1	1
243	-1	1	-1	-1	1	1	1	1	-1	1
244	1	1	-1	-1	1	1	1	1	1	-1
245	-1	-1	1	-1	1	1	1	1	-1	1
246	1	-1	1	-1	1	1	1	1	1	-1
247	-1	1	1	-1	1	1	1	1	1	-1
248	1	1	1	-1	1	1	1	1	-1	1
249	-1	-1	-1	1	1	1	1	1	-1	-1
250	1	-1	-1	1	1	1	1	1	1	1
251	-1	1	-1	1	1	1	1	1	1	1
252	1	1	-1	1	1	1	1	1	-1	-1
253	-1	-1	1	1	1	1	1	1	1	1
254	1	-1	1	1	1	1	1	1	-1	-1
255	-1	1	1	1	1	1	1	1	-1	-1
256	1	1	1	1	1	1	1	1	1	1

10 Coefficients, 2 levels, 1/8 Fractional Factorial Design

GENERAL DESIGN INFORMATION

128 runs, 10 factors,
Resolution V

Design generating information:

Generators

H=ABCDE J=ABCFG K=ABDF

Design										
Run	A	B	C	D	E	F	G	H	I	J
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	-1	-1	1	1	-1
3	-1	1	-1	-1	-1	-1	-1	1	1	-1
4	1	1	-1	-1	-1	-1	-1	-1	-1	1
5	-1	-1	1	-1	-1	-1	-1	1	1	1
6	1	-1	1	-1	-1	-1	-1	-1	-1	-1
7	-1	1	1	-1	-1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	-1	1	1	1
9	-1	-1	-1	1	-1	-1	-1	1	-1	-1
10	1	-1	-1	1	-1	-1	-1	-1	1	1
11	-1	1	-1	1	-1	-1	-1	-1	1	1
12	1	1	-1	1	-1	-1	-1	1	-1	-1
13	-1	-1	1	1	-1	-1	-1	-1	1	-1
14	1	-1	1	1	-1	-1	-1	1	-1	1
15	-1	1	1	1	-1	-1	-1	1	-1	1
16	1	1	1	1	-1	-1	-1	-1	1	-1
17	-1	-1	-1	-1	1	-1	-1	1	-1	1
18	1	-1	-1	-1	1	-1	-1	-1	1	-1
19	-1	1	-1	-1	1	-1	-1	-1	1	-1
20	1	1	-1	-1	1	-1	-1	1	-1	1
21	-1	-1	1	-1	1	-1	-1	-1	1	1
22	1	-1	1	-1	1	-1	-1	1	-1	-1
23	-1	1	1	-1	1	-1	-1	1	-1	-1
24	1	1	1	-1	1	-1	-1	-1	1	1
25	-1	-1	-1	1	1	-1	-1	-1	-1	-1
26	1	-1	-1	1	1	-1	-1	1	1	1
27	-1	1	-1	1	1	-1	-1	1	1	1
28	1	1	-1	1	1	-1	-1	-1	-1	-1
29	-1	-1	1	1	1	-1	-1	1	1	-1
30	1	-1	1	1	1	-1	-1	-1	-1	1
31	-1	1	1	1	1	-1	-1	-1	-1	1
32	1	1	1	1	1	-1	-1	1	1	-1
33	-1	-1	-1	-1	-1	1	-1	-1	1	-1
34	1	-1	-1	-1	-1	1	-1	1	-1	1
35	-1	1	-1	-1	-1	1	-1	1	-1	1
36	1	1	-1	-1	-1	1	-1	-1	1	-1
37	-1	-1	1	-1	-1	1	-1	1	-1	-1
38	1	-1	1	-1	-1	1	-1	-1	1	1
39	-1	1	1	-1	-1	1	-1	-1	1	1
40	1	1	1	-1	-1	1	-1	1	-1	-1

Design										
Run	A	B	C	D	E	F	G	H	I	J
41	-1	-1	-1	1	-1	1	-1	1	1	1
42	1	-1	-1	1	-1	1	-1	-1	-1	-1
43	-1	1	-1	1	-1	1	-1	-1	-1	-1
44	1	1	-1	1	-1	1	-1	1	1	1
45	-1	-1	1	1	-1	1	-1	-1	-1	1
46	1	-1	1	1	-1	1	-1	1	1	-1
47	-1	1	1	1	-1	1	-1	1	1	-1
48	1	1	1	1	-1	1	-1	-1	-1	1
49	-1	-1	-1	-1	1	1	-1	1	1	-1
50	1	-1	-1	-1	1	1	-1	-1	-1	1
51	-1	1	-1	-1	1	1	-1	-1	-1	1
52	1	1	-1	-1	1	1	-1	1	1	-1
53	-1	-1	1	-1	1	1	-1	-1	-1	-1
54	1	-1	1	-1	1	1	-1	1	1	1
55	-1	1	1	-1	1	1	-1	1	1	1
56	1	1	1	-1	1	1	-1	-1	-1	-1
57	-1	-1	-1	1	1	1	-1	-1	1	1
58	1	-1	-1	1	1	1	-1	1	-1	-1
59	-1	1	-1	1	1	1	-1	1	-1	-1
60	1	1	-1	1	1	1	-1	-1	1	1
61	-1	-1	1	1	1	1	-1	1	-1	1
62	1	-1	1	1	1	1	-1	-1	1	-1
63	-1	1	1	1	1	1	-1	-1	1	-1
64	1	1	1	1	1	1	-1	1	-1	1
65	-1	-1	-1	-1	-1	-1	1	-1	1	1
66	1	-1	-1	-1	-1	-1	1	1	-1	-1
67	-1	1	-1	-1	-1	-1	1	1	-1	-1
68	1	1	-1	-1	-1	-1	1	-1	1	1
69	-1	-1	1	-1	-1	-1	1	1	-1	1
70	1	-1	1	-1	-1	-1	1	-1	1	-1
71	-1	1	1	-1	-1	-1	1	-1	1	-1
72	1	1	1	-1	-1	-1	1	1	-1	1
73	-1	-1	-1	1	-1	-1	1	1	1	-1
74	1	-1	-1	1	-1	-1	1	-1	-1	1
75	-1	1	-1	1	-1	-1	1	-1	-1	1
76	1	1	-1	1	-1	-1	1	1	1	-1
77	-1	-1	1	1	-1	-1	1	-1	-1	-1
78	1	-1	1	1	-1	-1	1	1	1	1
79	-1	1	1	1	-1	-1	1	1	1	1
80	1	1	1	1	-1	-1	1	-1	-1	-1
81	-1	-1	-1	-1	1	-1	1	1	1	1
82	1	-1	-1	-1	1	-1	1	-1	-1	-1
83	-1	1	-1	-1	1	-1	1	-1	-1	-1
84	1	1	-1	-1	1	-1	1	1	1	1
85	-1	-1	1	-1	1	-1	1	-1	-1	1
86	1	-1	1	-1	1	-1	1	1	1	-1
87	-1	1	1	-1	1	-1	1	1	1	-1
88	1	1	1	-1	1	-1	1	-1	-1	1
89	-1	-1	-1	1	1	-1	1	-1	1	-1
90	1	-1	-1	1	1	-1	1	1	-1	1

Design										
Run	A	B	C	D	E	F	G	H	I	J
91	-1	1	-1	1	1	-1	1	1	-1	1
92	1	1	-1	1	1	-1	1	-1	1	-1
93	-1	-1	1	1	1	-1	1	1	-1	-1
94	1	-1	1	1	1	-1	1	-1	1	1
95	-1	1	1	1	1	-1	1	-1	1	1
96	1	1	1	1	1	-1	1	1	-1	-1
97	-1	-1	-1	-1	-1	1	1	-1	-1	-1
98	1	-1	-1	-1	-1	1	1	1	1	1
99	-1	1	-1	-1	-1	1	1	1	1	1
100	1	1	-1	-1	-1	1	1	-1	-1	-1
101	-1	-1	1	-1	-1	1	1	1	1	-1
102	1	-1	1	-1	-1	1	1	-1	-1	1
103	-1	1	1	-1	-1	1	1	-1	-1	1
104	1	1	1	-1	-1	1	1	1	1	-1
105	-1	-1	-1	1	-1	1	1	1	-1	1
106	1	-1	-1	1	-1	1	1	-1	1	-1
107	-1	1	-1	1	-1	1	1	-1	1	-1
108	1	1	-1	1	-1	1	1	1	-1	1
109	-1	-1	1	1	-1	1	1	-1	1	1
110	1	-1	1	1	-1	1	1	1	-1	-1
111	-1	1	1	1	-1	1	1	1	-1	-1
112	1	1	1	1	-1	1	1	-1	1	1
113	-1	-1	-1	-1	1	1	1	1	-1	-1
114	1	-1	-1	-1	1	1	1	-1	1	1
115	-1	1	-1	-1	1	1	1	-1	1	1
116	1	1	-1	-1	1	1	1	1	-1	-1
117	-1	-1	1	-1	1	1	1	-1	1	-1
118	1	-1	1	-1	1	1	1	1	-1	1
119	-1	1	1	-1	1	1	1	1	-1	1
120	1	1	1	-1	1	1	1	-1	1	-1
121	-1	-1	-1	1	1	1	1	-1	-1	1
122	1	-1	-1	1	1	1	1	1	1	-1
123	-1	1	-1	1	1	1	1	1	1	-1
124	1	1	-1	1	1	1	1	-1	-1	1
125	-1	-1	1	1	1	1	1	1	1	1
126	1	-1	1	1	1	1	1	-1	-1	-1
127	-1	1	1	1	1	1	1	-1	-1	-1
128	1	1	1	1	1	1	1	1	1	1

10 Coefficients, 2 levels, 1/16 Fractional Factorial Design

GENERAL DESIGN INFORMATION

64 runs, 10 factors,
Resolution IV

Design generating information:

Generators

G=ABC H=ABDE J=ABDF K=ACEF

WARNING

CONFOUNDING

AB=CG AC=BG AG=BC EF=HJ EH=FJ EJ=FH

Design										
Run	A	B	C	D	E	F	G	H	I	J
1	-1	-1	-1	-1	-1	-1	-1	1	1	1
2	1	-1	-1	-1	-1	-1	1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	1	-1	-1	1
4	1	1	-1	-1	-1	-1	-1	1	1	-1
5	-1	-1	1	-1	-1	-1	1	1	1	-1
6	1	-1	1	-1	-1	-1	-1	-1	-1	1
7	-1	1	1	-1	-1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	1	1	1	1
9	-1	-1	-1	1	-1	-1	-1	-1	-1	1
10	1	-1	-1	1	-1	-1	1	1	1	-1
11	-1	1	-1	1	-1	-1	1	1	1	1
12	1	1	-1	1	-1	-1	-1	-1	-1	-1
13	-1	-1	1	1	-1	-1	1	-1	-1	-1
14	1	-1	1	1	-1	-1	-1	1	1	1
15	-1	1	1	1	-1	-1	-1	1	1	-1
16	1	1	1	1	-1	-1	1	-1	-1	1
17	-1	-1	-1	-1	1	-1	-1	-1	1	-1
18	1	-1	-1	-1	1	-1	1	1	-1	1
19	-1	1	-1	-1	1	-1	1	1	-1	-1
20	1	1	-1	-1	1	-1	-1	-1	1	1
21	-1	-1	1	-1	1	-1	1	-1	1	1
22	1	-1	1	-1	1	-1	-1	1	-1	-1
23	-1	1	1	-1	1	-1	-1	1	-1	1
24	1	1	1	-1	1	-1	1	-1	1	-1
25	-1	-1	-1	1	1	-1	-1	1	-1	-1
26	1	-1	-1	1	1	-1	1	-1	1	1
27	-1	1	-1	1	1	-1	1	-1	1	-1
28	1	1	-1	1	1	-1	-1	1	-1	1
29	-1	-1	1	1	1	-1	1	1	-1	1
30	1	-1	1	1	1	-1	-1	-1	1	-1
31	-1	1	1	1	1	-1	-1	-1	1	1
32	1	1	1	1	1	-1	1	1	-1	-1

Design										
Run	A	B	C	D	E	F	G	H	I	J
33	-1	-1	-1	-1	-1	1	-1	1	-1	-1
34	1	-1	-1	-1	-1	1	1	-1	1	1
35	-1	1	-1	-1	-1	1	1	-1	1	-1
36	1	1	-1	-1	-1	1	-1	1	-1	1
37	-1	-1	1	-1	-1	1	1	1	-1	1
38	1	-1	1	-1	-1	1	-1	-1	1	-1
39	-1	1	1	-1	-1	1	-1	-1	1	1
40	1	1	1	-1	-1	1	1	1	-1	-1
41	-1	-1	-1	1	-1	1	-1	-1	1	-1
42	1	-1	-1	1	-1	1	1	1	-1	1
43	-1	1	-1	1	-1	1	1	1	-1	-1
44	1	1	-1	1	-1	1	-1	-1	1	1
45	-1	-1	1	1	-1	1	1	-1	1	1
46	1	-1	1	1	-1	1	-1	1	-1	-1
47	-1	1	1	1	-1	1	-1	1	-1	1
48	1	1	1	1	-1	1	1	-1	1	-1
49	-1	-1	-1	-1	1	1	-1	-1	-1	1
50	1	-1	-1	-1	1	1	1	1	1	-1
51	-1	1	-1	-1	1	1	1	1	1	1
52	1	1	-1	-1	1	1	-1	-1	-1	-1
53	-1	-1	1	-1	1	1	1	-1	-1	-1
54	1	-1	1	-1	1	1	-1	1	1	1
55	-1	1	1	-1	1	1	-1	1	1	-1
56	1	1	1	-1	1	1	1	-1	-1	1
57	-1	-1	-1	1	1	1	-1	1	1	1
58	1	-1	-1	1	1	1	1	-1	-1	-1
59	-1	1	-1	1	1	1	1	-1	-1	1
60	1	1	-1	1	1	1	-1	1	1	-1
61	-1	-1	1	1	1	1	1	1	1	-1
62	1	-1	1	1	1	1	-1	-1	-1	1
63	-1	1	1	1	1	1	-1	-1	-1	-1
64	1	1	1	1	1	1	1	1	1	1

11 Coefficients, 2 levels, 1/8 Fractional Factorial Design

GENERAL DESIGN INFORMATION

256 runs, 11 factors,
Resolution VI

Design generating information:

Generators

J=ABCDEFG K=ABCDH L=ABEFH

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	-1	-1	-1	-1	1	1	1
3	-1	1	-1	-1	-1	-1	-1	-1	1	1	1
4	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	1	-1	-1	-1	-1	-1	1	1	-1
6	1	-1	1	-1	-1	-1	-1	-1	-1	-1	1
7	-1	1	1	-1	-1	-1	-1	-1	-1	-1	1
8	1	1	1	-1	-1	-1	-1	-1	1	1	-1
9	-1	-1	-1	1	-1	-1	-1	-1	1	1	-1
10	1	-1	-1	1	-1	-1	-1	-1	-1	-1	1
11	-1	1	-1	1	-1	-1	-1	-1	-1	-1	1
12	1	1	-1	1	-1	-1	-1	-1	1	1	-1
13	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
14	1	-1	1	1	-1	-1	-1	-1	1	1	1
15	-1	1	1	1	-1	-1	-1	-1	1	1	1
16	1	1	1	1	-1	-1	-1	-1	-1	-1	-1
17	-1	-1	-1	-1	1	-1	-1	-1	1	-1	1
18	1	-1	-1	-1	1	-1	-1	-1	-1	1	-1
19	-1	1	-1	-1	1	-1	-1	-1	-1	1	-1
20	1	1	-1	-1	1	-1	-1	-1	1	-1	1
21	-1	-1	1	-1	1	-1	-1	-1	-1	1	1
22	1	-1	1	-1	1	-1	-1	-1	1	-1	-1
23	-1	1	1	-1	1	-1	-1	-1	1	-1	-1
24	1	1	1	-1	1	-1	-1	-1	-1	1	1
25	-1	-1	-1	1	1	-1	-1	-1	-1	1	1
26	1	-1	-1	1	1	-1	-1	-1	1	-1	-1
27	-1	1	-1	1	1	-1	-1	-1	1	-1	-1
28	1	1	-1	1	1	-1	-1	-1	-1	1	1
29	-1	-1	1	1	1	-1	-1	-1	1	-1	1
30	1	-1	1	1	1	-1	-1	-1	-1	1	-1
31	-1	1	1	1	1	-1	-1	-1	-1	1	-1
32	1	1	1	1	1	-1	-1	-1	1	-1	1
33	-1	-1	-1	-1	-1	1	-1	-1	1	-1	1
34	1	-1	-1	-1	-1	1	-1	-1	-1	1	-1
35	-1	1	-1	-1	-1	1	-1	-1	-1	1	-1
36	1	1	-1	-1	-1	1	-1	-1	1	-1	1
37	-1	-1	1	-1	-1	1	-1	-1	-1	1	1
38	1	-1	1	-1	-1	1	-1	-1	1	-1	-1
39	-1	1	1	-1	-1	1	-1	-1	1	-1	-1
40	1	1	1	-1	-1	1	-1	-1	-1	1	1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
41	-1	-1	-1	1	-1	1	-1	-1	-1	1	1
42	1	-1	-1	1	-1	1	-1	-1	1	-1	-1
43	-1	1	-1	1	-1	1	-1	-1	1	-1	-1
44	1	1	-1	1	-1	1	-1	-1	-1	1	1
45	-1	-1	1	1	-1	1	-1	-1	1	-1	1
46	1	-1	1	1	-1	1	-1	-1	-1	1	-1
47	-1	1	1	1	-1	1	-1	-1	-1	1	-1
48	1	1	1	1	-1	1	-1	-1	1	-1	1
49	-1	-1	-1	-1	1	1	-1	-1	-1	-1	-1
50	1	-1	-1	-1	1	1	-1	-1	1	1	1
51	-1	1	-1	-1	1	1	-1	-1	1	1	1
52	1	1	-1	-1	1	1	-1	-1	-1	-1	-1
53	-1	-1	1	-1	1	1	-1	-1	1	1	-1
54	1	-1	1	-1	1	1	-1	-1	-1	-1	1
55	-1	1	1	-1	1	1	-1	-1	-1	-1	1
56	1	1	1	-1	1	1	-1	-1	1	1	-1
57	-1	-1	-1	1	1	1	-1	-1	1	1	-1
58	1	-1	-1	1	1	1	-1	-1	-1	-1	1
59	-1	1	-1	1	1	1	-1	-1	-1	-1	1
60	1	1	-1	1	1	1	-1	-1	1	1	-1
61	-1	-1	1	1	1	1	-1	-1	-1	-1	-1
62	1	-1	1	1	1	1	-1	-1	1	1	1
63	-1	1	1	1	1	1	-1	-1	1	1	1
64	1	1	1	1	1	1	-1	-1	-1	-1	-1
65	-1	-1	-1	-1	-1	-1	1	-1	1	-1	-1
66	1	-1	-1	-1	-1	-1	1	-1	-1	1	1
67	-1	1	-1	-1	-1	-1	1	-1	-1	1	1
68	1	1	-1	-1	-1	-1	1	-1	1	-1	-1
69	-1	-1	1	-1	-1	-1	1	-1	-1	1	-1
70	1	-1	1	-1	-1	-1	1	-1	1	-1	1
71	-1	1	1	-1	-1	-1	1	-1	1	-1	1
72	1	1	1	-1	-1	-1	1	-1	-1	1	-1
73	-1	-1	-1	1	-1	-1	1	-1	-1	1	-1
74	1	-1	-1	1	-1	-1	1	-1	1	-1	1
75	-1	1	-1	1	-1	-1	1	-1	1	-1	1
76	1	1	-1	1	-1	-1	1	-1	-1	1	-1
77	-1	-1	1	1	-1	-1	1	-1	1	-1	-1
78	1	-1	1	1	-1	-1	1	-1	-1	1	1
79	-1	1	1	1	-1	-1	1	-1	-1	1	1
80	1	1	1	1	-1	-1	1	-1	1	-1	-1
81	-1	-1	-1	-1	1	-1	1	-1	-1	-1	1
82	1	-1	-1	-1	1	-1	1	-1	1	1	-1
83	-1	1	-1	-1	1	-1	1	-1	1	1	-1
84	1	1	-1	-1	1	-1	1	-1	-1	-1	1
85	-1	-1	1	-1	1	-1	1	-1	1	1	1
86	1	-1	1	-1	1	-1	1	-1	-1	-1	-1
87	-1	1	1	-1	1	-1	1	-1	-1	-1	-1
88	1	1	1	-1	1	-1	1	-1	1	1	1
89	-1	-1	-1	1	1	-1	1	-1	1	1	1
90	1	-1	-1	1	1	-1	1	-1	-1	-1	-1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
91	-1	1	-1	1	1	-1	1	-1	-1	-1	-1
92	1	1	-1	1	1	-1	1	-1	1	1	1
93	-1	-1	1	1	1	-1	1	-1	-1	-1	1
94	1	-1	1	1	1	-1	1	-1	1	1	-1
95	-1	1	1	1	1	-1	1	-1	1	1	-1
96	1	1	1	1	1	-1	1	-1	-1	-1	1
97	-1	-1	-1	-1	-1	1	1	-1	-1	-1	1
98	1	-1	-1	-1	-1	1	1	-1	1	1	-1
99	-1	1	-1	-1	-1	1	1	-1	1	1	-1
100	1	1	-1	-1	-1	1	1	-1	-1	-1	1
101	-1	-1	1	-1	-1	1	1	-1	1	1	1
102	1	-1	1	-1	-1	1	1	-1	-1	-1	-1
103	-1	1	1	-1	-1	1	1	-1	-1	-1	-1
104	1	1	1	-1	-1	1	1	-1	1	1	1
105	-1	-1	-1	1	-1	1	1	-1	1	1	1
106	1	-1	-1	1	-1	1	1	-1	-1	-1	-1
107	-1	1	-1	1	-1	1	1	-1	-1	-1	-1
108	1	1	-1	1	-1	1	1	-1	1	1	1
109	-1	-1	1	1	-1	1	1	-1	-1	-1	1
110	1	-1	1	1	-1	1	1	-1	1	1	-1
111	-1	1	1	1	-1	1	1	-1	1	1	-1
112	1	1	1	1	-1	1	1	-1	-1	-1	1
113	-1	-1	-1	-1	1	1	1	-1	1	-1	-1
114	1	-1	-1	-1	1	1	1	-1	-1	1	1
115	-1	1	-1	-1	1	1	1	-1	-1	1	1
116	1	1	-1	-1	1	1	1	-1	1	-1	-1
117	-1	-1	1	-1	1	1	1	-1	-1	1	-1
118	1	-1	1	-1	1	1	1	-1	1	-1	1
119	-1	1	1	-1	1	1	1	-1	1	-1	1
120	1	1	1	-1	1	1	1	-1	-1	1	-1
121	-1	-1	-1	1	1	1	1	-1	-1	1	-1
122	1	-1	-1	1	1	1	1	-1	1	-1	1
123	-1	1	-1	1	1	1	1	-1	1	-1	1
124	1	1	-1	1	1	1	1	-1	-1	1	-1
125	-1	-1	1	1	1	1	1	-1	1	-1	-1
126	1	-1	1	1	1	1	1	-1	-1	1	1
127	-1	1	1	1	1	1	1	-1	-1	1	1
128	1	1	1	1	1	1	1	-1	1	-1	-1
129	-1	-1	-1	-1	-1	-1	-1	1	-1	1	1
130	1	-1	-1	-1	-1	-1	-1	1	1	-1	-1
131	-1	1	-1	-1	-1	-1	-1	1	1	-1	-1
132	1	1	-1	-1	-1	-1	-1	1	-1	1	1
133	-1	-1	1	-1	-1	-1	-1	1	1	-1	1
134	1	-1	1	-1	-1	-1	-1	1	-1	1	-1
135	-1	1	1	-1	-1	-1	-1	1	-1	1	-1
136	1	1	1	-1	-1	-1	-1	1	1	-1	1
137	-1	-1	-1	1	-1	-1	-1	1	1	-1	1
138	1	-1	-1	1	-1	-1	-1	1	-1	1	-1
139	-1	1	-1	1	-1	-1	-1	1	-1	1	-1
140	1	1	-1	1	-1	-1	-1	1	1	-1	1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
141	-1	-1	1	1	-1	-1	-1	1	-1	1	1
142	1	-1	1	1	-1	-1	-1	1	1	-1	-1
143	-1	1	1	1	-1	-1	-1	1	1	-1	-1
144	1	1	1	1	-1	-1	-1	1	-1	1	1
145	-1	-1	-1	-1	1	-1	-1	1	1	1	-1
146	1	-1	-1	-1	1	-1	-1	1	-1	-1	1
147	-1	1	-1	-1	1	-1	-1	1	-1	-1	1
148	1	1	-1	-1	1	-1	-1	1	1	1	-1
149	-1	-1	1	-1	1	-1	-1	1	-1	-1	-1
150	1	-1	1	-1	1	-1	-1	1	1	1	1
151	-1	1	1	-1	1	-1	-1	1	1	1	1
152	1	1	1	-1	1	-1	-1	1	-1	-1	-1
153	-1	-1	-1	1	1	-1	-1	1	-1	-1	-1
154	1	-1	-1	1	1	-1	-1	1	1	1	1
155	-1	1	-1	1	1	-1	-1	1	1	1	1
156	1	1	-1	1	1	-1	-1	1	-1	-1	-1
157	-1	-1	1	1	1	-1	-1	1	1	1	-1
158	1	-1	1	1	1	-1	-1	1	-1	-1	1
159	-1	1	1	1	1	-1	-1	1	-1	-1	1
160	1	1	1	1	1	-1	-1	1	1	1	-1
161	-1	-1	-1	-1	-1	1	-1	1	1	1	-1
162	1	-1	-1	-1	-1	1	-1	1	-1	-1	1
163	-1	1	-1	-1	-1	1	-1	1	-1	-1	1
164	1	1	-1	-1	-1	1	-1	1	1	1	-1
165	-1	-1	1	-1	-1	1	-1	1	-1	-1	-1
166	1	-1	1	-1	-1	1	-1	1	1	1	1
167	-1	1	1	-1	-1	1	-1	1	1	1	1
168	1	1	1	-1	-1	1	-1	1	-1	-1	-1
169	-1	-1	-1	1	-1	1	-1	1	-1	-1	-1
170	1	-1	-1	1	-1	1	-1	1	1	1	1
171	-1	1	-1	1	-1	1	-1	1	1	1	1
172	1	1	-1	1	-1	1	-1	1	-1	-1	-1
173	-1	-1	1	1	-1	1	-1	1	1	1	-1
174	1	-1	1	1	-1	1	-1	1	-1	-1	1
175	-1	1	1	1	-1	1	-1	1	-1	-1	1
176	1	1	1	1	-1	1	-1	1	1	1	-1
177	-1	-1	-1	-1	1	1	-1	1	-1	1	1
178	1	-1	-1	-1	1	1	-1	1	1	-1	-1
179	-1	1	-1	-1	1	1	-1	1	1	-1	-1
180	1	1	-1	-1	1	1	-1	1	-1	1	1
181	-1	-1	1	-1	1	1	-1	1	1	-1	1
182	1	-1	1	-1	1	1	-1	1	-1	1	-1
183	-1	1	1	-1	1	1	-1	1	-1	1	-1
184	1	1	1	-1	1	1	-1	1	1	-1	1
185	-1	-1	-1	1	1	1	-1	1	1	-1	1
186	1	-1	-1	1	1	1	-1	1	-1	1	-1
187	-1	1	-1	1	1	1	-1	1	-1	1	-1
188	1	1	-1	1	1	1	-1	1	1	-1	1
189	-1	-1	1	1	1	1	-1	1	-1	1	1
190	1	-1	1	1	1	1	-1	1	1	-1	-1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
191	-1	1	1	1	1	1	-1	1	1	-1	-1
192	1	1	1	1	1	1	-1	1	-1	1	1
193	-1	-1	-1	-1	-1	-1	1	1	1	1	1
194	1	-1	-1	-1	-1	-1	1	1	-1	-1	-1
195	-1	1	-1	-1	-1	-1	1	1	-1	-1	-1
196	1	1	-1	-1	-1	-1	1	1	1	1	1
197	-1	-1	1	-1	-1	-1	1	1	-1	-1	1
198	1	-1	1	-1	-1	-1	1	1	1	1	-1
199	-1	1	1	-1	-1	-1	1	1	1	1	-1
200	1	1	1	-1	-1	-1	1	1	-1	-1	1
201	-1	-1	-1	1	-1	-1	1	1	-1	-1	1
202	1	-1	-1	1	-1	-1	1	1	1	1	-1
203	-1	1	-1	1	-1	-1	1	1	1	1	-1
204	1	1	-1	1	-1	-1	1	1	-1	-1	1
205	-1	-1	1	1	-1	-1	1	1	1	1	1
206	1	-1	1	1	-1	-1	1	1	-1	-1	-1
207	-1	1	1	1	-1	-1	1	1	-1	-1	-1
208	1	1	1	1	-1	-1	1	1	1	1	1
209	-1	-1	-1	-1	1	-1	1	1	-1	1	-1
210	1	-1	-1	-1	1	-1	1	1	1	-1	1
211	-1	1	-1	-1	1	-1	1	1	1	-1	1
212	1	1	-1	-1	1	-1	1	1	-1	1	-1
213	-1	-1	1	-1	1	-1	1	1	1	-1	-1
214	1	-1	1	-1	1	-1	1	1	-1	1	1
215	-1	1	1	-1	1	-1	1	1	-1	1	1
216	1	1	1	-1	1	-1	1	1	1	-1	-1
217	-1	-1	-1	1	1	-1	1	1	1	-1	-1
218	1	-1	-1	1	1	-1	1	1	-1	1	1
219	-1	1	-1	1	1	-1	1	1	-1	1	1
220	1	1	-1	1	1	-1	1	1	1	-1	-1
221	-1	-1	1	1	1	-1	1	1	-1	1	-1
222	1	-1	1	1	1	-1	1	1	1	-1	1
223	-1	1	1	1	1	-1	1	1	1	-1	1
224	1	1	1	1	1	-1	1	1	-1	1	-1
225	-1	-1	-1	-1	-1	1	1	1	-1	1	-1
226	1	-1	-1	-1	-1	1	1	1	1	-1	1
227	-1	1	-1	-1	-1	1	1	1	1	-1	1
228	1	1	-1	-1	-1	1	1	1	-1	1	-1
229	-1	-1	1	-1	-1	1	1	1	1	-1	-1
230	1	-1	1	-1	-1	1	1	1	-1	1	1
231	-1	1	1	-1	-1	1	1	1	-1	1	1
232	1	1	1	-1	-1	1	1	1	1	-1	-1
233	-1	-1	-1	1	-1	1	1	1	1	-1	-1
234	1	-1	-1	1	-1	1	1	1	-1	1	1
235	-1	1	-1	1	-1	1	1	1	-1	1	1
236	1	1	-1	1	-1	1	1	1	1	-1	-1
237	-1	-1	1	1	-1	1	1	1	-1	1	-1
238	1	-1	1	1	-1	1	1	1	1	-1	1
239	-1	1	1	1	-1	1	1	1	1	-1	1
240	1	1	1	1	-1	1	1	1	-1	1	-1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
241	-1	-1	-1	-1	1	1	1	1	1	1	1
242	1	-1	-1	-1	1	1	1	1	-1	-1	-1
243	-1	1	-1	-1	1	1	1	1	-1	-1	-1
244	1	1	-1	-1	1	1	1	1	1	1	1
245	-1	-1	1	-1	1	1	1	1	-1	-1	1
246	1	-1	1	-1	1	1	1	1	1	1	-1
247	-1	1	1	-1	1	1	1	1	1	1	-1
248	1	1	1	-1	1	1	1	1	-1	-1	1
249	-1	-1	-1	1	1	1	1	1	-1	-1	1
250	1	-1	-1	1	1	1	1	1	1	1	-1
251	-1	1	-1	1	1	1	1	1	1	1	-1
252	1	1	-1	1	1	1	1	1	-1	-1	1
253	-1	-1	1	1	1	1	1	1	1	1	1
254	1	-1	1	1	1	1	1	1	-1	-1	-1
255	-1	1	1	1	1	1	1	1	-1	-1	-1
256	1	1	1	1	1	1	1	1	1	1	1

11 Coefficients, 2 levels, 1/8 Fractional Factorial Design

GENERAL DESIGN INFORMATION

128 runs, 11 factors,
Resolution V

Design generating information:

Generators

H=ABCDE J=ABCFG K=ABDF L=ACEG

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1	-1	-1	1	1	-1	-1
3	-1	1	-1	-1	-1	-1	-1	1	1	-1	1
4	1	1	-1	-1	-1	-1	-1	-1	-1	1	-1
5	-1	-1	1	-1	-1	-1	-1	1	1	1	-1
6	1	-1	1	-1	-1	-1	-1	-1	-1	-1	1
7	-1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	-1	1	1	1	1
9	-1	-1	-1	1	-1	-1	-1	1	-1	-1	1
10	1	-1	-1	1	-1	-1	-1	-1	1	1	-1
11	-1	1	-1	1	-1	-1	-1	-1	1	1	1
12	1	1	-1	1	-1	-1	-1	1	-1	-1	-1
13	-1	-1	1	1	-1	-1	-1	-1	1	-1	-1
14	1	-1	1	1	-1	-1	-1	1	-1	1	1
15	-1	1	1	1	-1	-1	-1	1	-1	1	-1
16	1	1	1	1	-1	-1	-1	-1	1	-1	1
17	-1	-1	-1	-1	1	-1	-1	1	-1	1	-1
18	1	-1	-1	-1	1	-1	-1	-1	1	-1	1
19	-1	1	-1	-1	1	-1	-1	-1	1	-1	-1
20	1	1	-1	-1	1	-1	-1	1	-1	1	1
21	-1	-1	1	-1	1	-1	-1	-1	1	1	1
22	1	-1	1	-1	1	-1	-1	1	-1	-1	-1
23	-1	1	1	-1	1	-1	-1	1	-1	-1	1
24	1	1	1	-1	1	-1	-1	-1	1	1	-1
25	-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1
26	1	-1	-1	1	1	-1	-1	1	1	1	1
27	-1	1	-1	1	1	-1	-1	1	1	1	-1
28	1	1	-1	1	1	-1	-1	-1	-1	-1	1
29	-1	-1	1	1	1	-1	-1	1	1	-1	1
30	1	-1	1	1	1	-1	-1	-1	-1	1	-1
31	-1	1	1	1	1	-1	-1	-1	-1	1	1
32	1	1	1	1	1	-1	-1	1	1	-1	-1
33	-1	-1	-1	-1	-1	1	-1	-1	1	-1	1
34	1	-1	-1	-1	-1	1	-1	1	-1	1	-1
35	-1	1	-1	-1	-1	1	-1	1	-1	1	1
36	1	1	-1	-1	-1	1	-1	-1	1	-1	-1
37	-1	-1	1	-1	-1	1	-1	1	-1	-1	-1
38	1	-1	1	-1	-1	1	-1	-1	1	1	1
39	-1	1	1	-1	-1	1	-1	-1	1	1	-1
40	1	1	1	-1	-1	1	-1	1	-1	-1	1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
41	-1	-1	-1	1	-1	1	-1	1	1	1	1
42	1	-1	-1	1	-1	1	-1	-1	-1	-1	-1
43	-1	1	-1	1	-1	1	-1	-1	-1	-1	1
44	1	1	-1	1	-1	1	-1	1	1	1	-1
45	-1	-1	1	1	-1	1	-1	-1	-1	1	-1
46	1	-1	1	1	-1	1	-1	1	1	-1	1
47	-1	1	1	1	-1	1	-1	1	1	-1	-1
48	1	1	1	1	-1	1	-1	-1	-1	1	1
49	-1	-1	-1	-1	1	1	-1	1	1	-1	-1
50	1	-1	-1	-1	1	1	-1	-1	-1	1	1
51	-1	1	-1	-1	1	1	-1	-1	-1	1	-1
52	1	1	-1	-1	1	1	-1	1	1	-1	1
53	-1	-1	1	-1	1	1	-1	-1	-1	-1	1
54	1	-1	1	-1	1	1	-1	1	1	1	-1
55	-1	1	1	-1	1	1	-1	1	1	1	1
56	1	1	1	-1	1	1	-1	-1	-1	-1	-1
57	-1	-1	-1	1	1	1	-1	-1	1	1	-1
58	1	-1	-1	1	1	1	-1	1	-1	-1	1
59	-1	1	-1	1	1	1	-1	1	-1	-1	-1
60	1	1	-1	1	1	1	-1	-1	1	1	1
61	-1	-1	1	1	1	1	-1	1	-1	1	1
62	1	-1	1	1	1	1	-1	-1	1	-1	-1
63	-1	1	1	1	1	1	-1	-1	1	-1	1
64	1	1	1	1	1	1	-1	1	-1	1	-1
65	-1	-1	-1	-1	-1	-1	1	-1	1	1	-1
66	1	-1	-1	-1	-1	-1	1	1	-1	-1	1
67	-1	1	-1	-1	-1	-1	1	1	-1	-1	-1
68	1	1	-1	-1	-1	-1	1	-1	1	1	1
69	-1	-1	1	-1	-1	-1	1	1	-1	1	1
70	1	-1	1	-1	-1	-1	1	-1	1	-1	-1
71	-1	1	1	-1	-1	-1	1	-1	1	-1	1
72	1	1	1	-1	-1	-1	1	1	-1	1	-1
73	-1	-1	-1	1	-1	-1	1	1	1	-1	-1
74	1	-1	-1	1	-1	-1	1	-1	-1	1	1
75	-1	1	-1	1	-1	-1	1	-1	-1	1	-1
76	1	1	-1	1	-1	-1	1	1	1	-1	1
77	-1	-1	1	1	-1	-1	1	-1	-1	-1	1
78	1	-1	1	1	-1	-1	1	1	1	1	-1
79	-1	1	1	1	-1	-1	1	1	1	1	1
80	1	1	1	1	-1	-1	1	-1	-1	-1	-1
81	-1	-1	-1	-1	1	-1	1	1	1	1	1
82	1	-1	-1	-1	1	-1	1	-1	-1	-1	-1
83	-1	1	-1	-1	1	-1	1	-1	-1	-1	1
84	1	1	-1	-1	1	-1	1	1	1	1	-1
85	-1	-1	1	-1	1	-1	1	-1	-1	1	-1
86	1	-1	1	-1	1	-1	1	1	1	-1	1
87	-1	1	1	-1	1	-1	1	1	1	-1	-1
88	1	1	1	-1	1	-1	1	-1	-1	1	1
89	-1	-1	-1	1	1	-1	1	-1	1	-1	1
90	1	-1	-1	1	1	-1	1	1	-1	1	-1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
91	-1	1	-1	1	1	-1	1	1	-1	1	1
92	1	1	-1	1	1	-1	1	-1	1	-1	-1
93	-1	-1	1	1	1	-1	1	1	-1	-1	-1
94	1	-1	1	1	1	-1	1	-1	1	1	1
95	-1	1	1	1	1	-1	1	-1	1	1	-1
96	1	1	1	1	1	-1	1	1	-1	-1	1
97	-1	-1	-1	-1	-1	1	1	-1	-1	-1	-1
98	1	-1	-1	-1	-1	1	1	1	1	1	1
99	-1	1	-1	-1	-1	1	1	1	1	1	-1
100	1	1	-1	-1	-1	1	1	-1	-1	-1	1
101	-1	-1	1	-1	-1	1	1	1	1	-1	1
102	1	-1	1	-1	-1	1	1	-1	-1	1	-1
103	-1	1	1	-1	-1	1	1	-1	-1	1	1
104	1	1	1	-1	-1	1	1	1	1	-1	-1
105	-1	-1	-1	1	-1	1	1	1	-1	1	-1
106	1	-1	-1	1	-1	1	1	-1	1	-1	1
107	-1	1	-1	1	-1	1	1	-1	1	-1	-1
108	1	1	-1	1	-1	1	1	1	-1	1	1
109	-1	-1	1	1	-1	1	1	-1	1	1	1
110	1	-1	1	1	-1	1	1	1	-1	-1	-1
111	-1	1	1	1	-1	1	1	1	-1	-1	1
112	1	1	1	1	-1	1	1	-1	1	1	-1
113	-1	-1	-1	-1	1	1	1	1	-1	-1	1
114	1	-1	-1	-1	1	1	1	-1	1	1	-1
115	-1	1	-1	-1	1	1	1	-1	1	1	1
116	1	1	-1	-1	1	1	1	1	-1	-1	-1
117	-1	-1	1	-1	1	1	1	-1	1	-1	-1
118	1	-1	1	-1	1	1	1	1	-1	1	1
119	-1	1	1	-1	1	1	1	1	-1	1	-1
120	1	1	1	-1	1	1	1	-1	1	-1	1
121	-1	-1	-1	1	1	1	1	-1	-1	1	1
122	1	-1	-1	1	1	1	1	1	1	-1	-1
123	-1	1	-1	1	1	1	1	1	1	-1	1
124	1	1	-1	1	1	1	1	-1	-1	1	-1
125	-1	-1	1	1	1	1	1	1	1	1	-1
126	1	-1	1	1	1	1	1	-1	-1	-1	1
127	-1	1	1	1	1	1	1	-1	-1	-1	-1
128	1	1	1	1	1	1	1	1	1	1	1

11 Coefficients, 2 levels, 1/32 Fractional Factorial Design

GENERAL DESIGN INFORMATION

64 runs, 11 factors,
Resolution IV

Design generating information:

Generators

G=ABC H=ABD J=ACDE K=ACDF L=ABEF

WARNING

CONFOUNDING

AB=CG=DH AC=BG AD=BH AG=BC AH=BD

CD=GH CH=DG EF=JK EJ=FK EK=FJ

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1
2	1	-1	-1	-1	-1	-1	1	1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	1	1	1	1	-1
4	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1
5	-1	-1	1	-1	-1	-1	1	-1	-1	-1	1
6	1	-1	1	-1	-1	-1	-1	1	1	1	-1
7	-1	1	1	-1	-1	-1	-1	1	-1	-1	-1
8	1	1	1	-1	-1	-1	1	-1	1	1	1
9	-1	-1	-1	1	-1	-1	-1	1	-1	-1	1
10	1	-1	-1	1	-1	-1	1	-1	1	1	-1
11	-1	1	-1	1	-1	-1	1	-1	-1	-1	-1
12	1	1	-1	1	-1	-1	-1	1	1	1	1
13	-1	-1	1	1	-1	-1	1	1	1	1	1
14	1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1	-1	1	1	-1
16	1	1	1	1	-1	-1	1	1	-1	-1	1
17	-1	-1	-1	-1	1	-1	-1	-1	-1	1	-1
18	1	-1	-1	-1	1	-1	1	1	1	-1	1
19	-1	1	-1	-1	1	-1	1	1	-1	1	1
20	1	1	-1	-1	1	-1	-1	-1	1	-1	-1
21	-1	-1	1	-1	1	-1	1	-1	1	-1	-1
22	1	-1	1	-1	1	-1	-1	1	-1	1	1
23	-1	1	1	-1	1	-1	-1	1	1	-1	1
24	1	1	1	-1	1	-1	1	-1	-1	1	-1
25	-1	-1	-1	1	1	-1	-1	1	1	-1	-1
26	1	-1	-1	1	1	-1	1	-1	-1	1	1
27	-1	1	-1	1	1	-1	1	-1	1	-1	1
28	1	1	-1	1	1	-1	-1	1	-1	1	-1
29	-1	-1	1	1	1	-1	1	1	-1	1	-1
30	1	-1	1	1	1	-1	-1	-1	1	-1	1
31	-1	1	1	1	1	-1	-1	-1	-1	1	1
32	1	1	1	1	1	-1	1	1	1	-1	-1

Design											
Run	A	B	C	D	E	F	G	H	I	J	K
33	-1	-1	-1	-1	-1	1	-1	-1	1	-1	-1
34	1	-1	-1	-1	-1	1	1	1	-1	1	1
35	-1	1	-1	-1	-1	1	1	1	1	-1	1
36	1	1	-1	-1	-1	1	-1	-1	-1	1	-1
37	-1	-1	1	-1	-1	1	1	-1	-1	1	-1
38	1	-1	1	-1	-1	1	-1	1	1	-1	1
39	-1	1	1	-1	-1	1	-1	1	-1	1	1
40	1	1	1	-1	-1	1	1	-1	1	-1	-1
41	-1	-1	-1	1	-1	1	-1	1	-1	1	-1
42	1	-1	-1	1	-1	1	1	-1	1	-1	1
43	-1	1	-1	1	-1	1	1	-1	-1	1	1
44	1	1	-1	1	-1	1	-1	1	1	-1	-1
45	-1	-1	1	1	-1	1	1	1	1	-1	-1
46	1	-1	1	1	-1	1	-1	-1	-1	1	1
47	-1	1	1	1	-1	1	-1	-1	1	-1	1
48	1	1	1	1	-1	1	1	1	-1	1	-1
49	-1	-1	-1	-1	1	1	-1	-1	-1	-1	1
50	1	-1	-1	-1	1	1	1	1	1	1	-1
51	-1	1	-1	-1	1	1	1	1	-1	-1	-1
52	1	1	-1	-1	1	1	-1	-1	1	1	1
53	-1	-1	1	-1	1	1	1	-1	1	1	1
54	1	-1	1	-1	1	1	-1	1	-1	-1	-1
55	-1	1	1	-1	1	1	-1	1	1	1	-1
56	1	1	1	-1	1	1	1	-1	-1	-1	1
57	-1	-1	-1	1	1	1	-1	1	1	1	1
58	1	-1	-1	1	1	1	1	-1	-1	-1	-1
59	-1	1	-1	1	1	1	1	-1	1	1	-1
60	1	1	-1	1	1	1	-1	1	-1	-1	1
61	-1	-1	1	1	1	1	1	1	-1	-1	1
62	1	-1	1	1	1	1	-1	-1	1	1	-1
63	-1	1	1	1	1	1	-1	-1	-1	-1	-1
64	1	1	1	1	1	1	1	1	1	1	1

12 Coefficients, 2 levels, 1/16 Fractional Factorial Design

GENERAL DESIGN INFORMATION

256 runs, 12 factors,
Resolution VI

Design generating information:

Generators

J=ABCDEFGH K=ABCDH L=ABEFH M=ACEGH

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1
3	-1	1	-1	-1	-1	-1	-1	-1	1	1	1	-1
4	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1
5	-1	-1	1	-1	-1	-1	-1	-1	1	1	-1	1
6	1	-1	1	-1	-1	-1	-1	-1	-1	-1	1	-1
7	-1	1	1	-1	-1	-1	-1	-1	-1	-1	1	1
8	1	1	1	-1	-1	-1	-1	-1	1	1	-1	-1
9	-1	-1	-1	1	-1	-1	-1	-1	1	1	-1	-1
10	1	-1	-1	1	-1	-1	-1	-1	-1	-1	1	1
11	-1	1	-1	1	-1	-1	-1	-1	-1	-1	1	-1
12	1	1	-1	1	-1	-1	-1	-1	1	1	-1	1
13	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1	1
14	1	-1	1	1	-1	-1	-1	-1	1	1	1	-1
15	-1	1	1	1	-1	-1	-1	-1	1	1	1	1
16	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
17	-1	-1	-1	-1	1	-1	-1	-1	1	-1	1	1
18	1	-1	-1	-1	1	-1	-1	-1	-1	1	-1	-1
19	-1	1	-1	-1	1	-1	-1	-1	-1	1	-1	1
20	1	1	-1	-1	1	-1	-1	-1	1	-1	1	-1
21	-1	-1	1	-1	1	-1	-1	-1	-1	1	1	-1
22	1	-1	1	-1	1	-1	-1	-1	1	-1	-1	1
23	-1	1	1	-1	1	-1	-1	-1	1	-1	-1	-1
24	1	1	1	-1	1	-1	-1	-1	-1	1	1	1
25	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	1
26	1	-1	-1	1	1	-1	-1	-1	1	-1	-1	-1
27	-1	1	-1	1	1	-1	-1	-1	1	-1	-1	1
28	1	1	-1	1	1	-1	-1	-1	-1	1	1	-1
29	-1	-1	1	1	1	-1	-1	-1	1	-1	1	-1
30	1	-1	1	1	1	-1	-1	-1	-1	1	-1	1
31	-1	1	1	1	1	-1	-1	-1	-1	1	-1	-1
32	1	1	1	1	1	-1	-1	-1	1	-1	1	1
33	-1	-1	-1	-1	-1	1	-1	-1	1	-1	1	-1
34	1	-1	-1	-1	-1	1	-1	-1	-1	1	-1	1
35	-1	1	-1	-1	-1	1	-1	-1	-1	1	-1	-1
36	1	1	-1	-1	-1	1	-1	-1	1	-1	1	1
37	-1	-1	1	-1	-1	1	-1	-1	-1	1	1	1
38	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	-1
39	-1	1	1	-1	-1	1	-1	-1	1	-1	-1	1
40	1	1	1	-1	-1	1	-1	-1	-1	1	1	-1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
41	-1	-1	-1	1	-1	1	-1	-1	-1	1	1	-1
42	1	-1	-1	1	-1	1	-1	-1	1	-1	-1	1
43	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	-1
44	1	1	-1	1	-1	1	-1	-1	-1	1	1	1
45	-1	-1	1	1	-1	1	-1	-1	1	-1	1	1
46	1	-1	1	1	-1	1	-1	-1	-1	1	-1	-1
47	-1	1	1	1	-1	1	-1	-1	-1	1	-1	1
48	1	1	1	1	-1	1	-1	-1	1	-1	1	-1
49	-1	-1	-1	-1	1	1	-1	-1	-1	-1	-1	1
50	1	-1	-1	-1	1	1	-1	-1	1	1	1	-1
51	-1	1	-1	-1	1	1	-1	-1	1	1	1	1
52	1	1	-1	-1	1	1	-1	-1	-1	-1	-1	-1
53	-1	-1	1	-1	1	1	-1	-1	1	1	-1	-1
54	1	-1	1	-1	1	1	-1	-1	-1	-1	1	1
55	-1	1	1	-1	1	1	-1	-1	-1	-1	1	-1
56	1	1	1	-1	1	1	-1	-1	1	1	-1	1
57	-1	-1	-1	1	1	1	-1	-1	1	1	-1	1
58	1	-1	-1	1	1	1	-1	-1	-1	-1	1	-1
59	-1	1	-1	1	1	1	-1	-1	-1	-1	1	1
60	1	1	-1	1	1	1	-1	-1	1	1	-1	-1
61	-1	-1	1	1	1	1	-1	-1	-1	-1	-1	-1
62	1	-1	1	1	1	1	-1	-1	1	1	1	1
63	-1	1	1	1	1	1	-1	-1	1	1	1	-1
64	1	1	1	1	1	1	-1	-1	-1	-1	-1	1
65	-1	-1	-1	-1	-1	-1	1	-1	1	-1	-1	1
66	1	-1	-1	-1	-1	-1	1	-1	-1	1	1	-1
67	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
68	1	1	-1	-1	-1	-1	1	-1	1	-1	-1	-1
69	-1	-1	1	-1	-1	-1	1	-1	-1	1	-1	-1
70	1	-1	1	-1	-1	-1	1	-1	1	-1	1	1
71	-1	1	1	-1	-1	-1	1	-1	1	-1	1	-1
72	1	1	1	-1	-1	-1	1	-1	-1	1	-1	1
73	-1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1
74	1	-1	-1	1	-1	-1	1	-1	1	-1	1	-1
75	-1	1	-1	1	-1	-1	1	-1	1	-1	1	1
76	1	1	-1	1	-1	-1	1	-1	-1	1	-1	-1
77	-1	-1	1	1	-1	-1	1	-1	1	-1	-1	-1
78	1	-1	1	1	-1	-1	1	-1	-1	1	1	1
79	-1	1	1	1	-1	-1	1	-1	-1	1	1	-1
80	1	1	1	1	-1	-1	1	-1	1	-1	-1	1
81	-1	-1	-1	-1	1	-1	1	-1	-1	-1	1	-1
82	1	-1	-1	-1	1	-1	1	-1	1	1	-1	1
83	-1	1	-1	-1	1	-1	1	-1	1	1	-1	-1
84	1	1	-1	-1	1	-1	1	-1	-1	-1	1	1
85	-1	-1	1	-1	1	-1	1	-1	1	1	1	1
86	1	-1	1	-1	1	-1	1	-1	-1	-1	-1	-1
87	-1	1	1	-1	1	-1	1	-1	-1	-1	-1	1
88	1	1	1	-1	1	-1	1	-1	1	1	1	-1
89	-1	-1	-1	1	1	-1	1	-1	1	1	1	-1
90	1	-1	-1	1	1	-1	1	-1	-1	-1	-1	1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
91	-1	1	-1	1	1	-1	1	-1	-1	-1	-1	-1
92	1	1	-1	1	1	-1	1	-1	1	1	1	1
93	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1
94	1	-1	1	1	1	-1	1	-1	1	1	-1	-1
95	-1	1	1	1	1	-1	1	-1	1	1	-1	1
96	1	1	1	1	1	-1	1	-1	-1	-1	1	-1
97	-1	-1	-1	-1	-1	1	1	-1	-1	-1	1	1
98	1	-1	-1	-1	-1	1	1	-1	1	1	-1	-1
99	-1	1	-1	-1	-1	1	1	-1	1	1	-1	1
100	1	1	-1	-1	-1	1	1	-1	-1	-1	1	-1
101	-1	-1	1	-1	-1	1	1	-1	1	1	1	-1
102	1	-1	1	-1	-1	1	1	-1	-1	-1	-1	1
103	-1	1	1	-1	-1	1	1	-1	-1	-1	-1	-1
104	1	1	1	-1	-1	1	1	-1	1	1	1	1
105	-1	-1	-1	1	-1	1	1	-1	1	1	1	1
106	1	-1	-1	1	-1	1	1	-1	-1	-1	-1	-1
107	-1	1	-1	1	-1	1	1	-1	-1	-1	-1	1
108	1	1	-1	1	-1	1	1	-1	1	1	1	-1
109	-1	-1	1	1	-1	1	1	-1	-1	-1	1	-1
110	1	-1	1	1	-1	1	1	-1	1	1	-1	1
111	-1	1	1	1	-1	1	1	-1	1	1	-1	-1
112	1	1	1	1	-1	1	1	-1	-1	-1	1	1
113	-1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1
114	1	-1	-1	-1	1	1	1	-1	-1	1	1	1
115	-1	1	-1	-1	1	1	1	-1	-1	1	1	-1
116	1	1	-1	-1	1	1	1	-1	1	-1	-1	1
117	-1	-1	1	-1	1	1	1	-1	-1	1	-1	1
118	1	-1	1	-1	1	1	1	-1	1	-1	1	-1
119	-1	1	1	-1	1	1	1	-1	1	-1	1	1
120	1	1	1	-1	1	1	1	-1	-1	1	-1	-1
121	-1	-1	-1	1	1	1	1	-1	-1	1	-1	-1
122	1	-1	-1	1	1	1	1	-1	1	-1	1	1
123	-1	1	-1	1	1	1	1	-1	1	-1	1	-1
124	1	1	-1	1	1	1	1	-1	-1	1	-1	1
125	-1	-1	1	1	1	1	1	-1	1	-1	-1	1
126	1	-1	1	1	1	1	1	-1	-1	1	1	-1
127	-1	1	1	1	1	1	1	-1	-1	1	1	1
128	1	1	1	1	1	1	1	-1	1	-1	-1	-1
129	-1	-1	-1	-1	-1	-1	-1	1	-1	1	1	1
130	1	-1	-1	-1	-1	-1	-1	1	1	-1	-1	-1
131	-1	1	-1	-1	-1	-1	-1	1	1	-1	-1	1
132	1	1	-1	-1	-1	-1	-1	1	-1	1	1	-1
133	-1	-1	1	-1	-1	-1	-1	1	1	-1	1	-1
134	1	-1	1	-1	-1	-1	-1	1	-1	1	-1	1
135	-1	1	1	-1	-1	-1	-1	1	-1	1	-1	-1
136	1	1	1	-1	-1	-1	-1	1	1	-1	1	1
137	-1	-1	-1	1	-1	-1	-1	1	1	-1	1	1
138	1	-1	-1	1	-1	-1	-1	1	-1	1	-1	-1
139	-1	1	-1	1	-1	-1	-1	1	-1	1	-1	1
140	1	1	-1	1	-1	-1	-1	1	1	-1	1	-1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
141	-1	-1	1	1	-1	-1	-1	1	-1	1	1	-1
142	1	-1	1	1	-1	-1	-1	1	1	-1	-1	1
143	-1	1	1	1	-1	-1	-1	1	1	-1	-1	-1
144	1	1	1	1	-1	-1	-1	1	-1	1	1	1
145	-1	-1	-1	-1	1	-1	-1	1	1	1	-1	-1
146	1	-1	-1	-1	1	-1	-1	1	-1	-1	1	1
147	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1
148	1	1	-1	-1	1	-1	-1	1	1	1	-1	1
149	-1	-1	1	-1	1	-1	-1	1	-1	-1	-1	1
150	1	-1	1	-1	1	-1	-1	1	1	1	1	-1
151	-1	1	1	-1	1	-1	-1	1	1	1	1	1
152	1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1
153	-1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1
154	1	-1	-1	1	1	-1	-1	1	1	1	1	1
155	-1	1	-1	1	1	-1	-1	1	1	1	1	-1
156	1	1	-1	1	1	-1	-1	1	-1	-1	-1	1
157	-1	-1	1	1	1	-1	-1	1	1	1	-1	1
158	1	-1	1	1	1	-1	-1	1	-1	-1	1	-1
159	-1	1	1	1	1	-1	-1	1	-1	-1	1	1
160	1	1	1	1	1	-1	-1	1	1	1	-1	-1
161	-1	-1	-1	-1	-1	1	-1	1	1	1	-1	1
162	1	-1	-1	-1	-1	1	-1	1	-1	-1	1	-1
163	-1	1	-1	-1	-1	1	-1	1	-1	-1	1	1
164	1	1	-1	-1	-1	1	-1	1	1	1	-1	-1
165	-1	-1	1	-1	-1	1	-1	1	-1	-1	-1	-1
166	1	-1	1	-1	-1	1	-1	1	1	1	1	1
167	-1	1	1	-1	-1	1	-1	1	1	1	1	-1
168	1	1	1	-1	-1	1	-1	1	-1	-1	-1	1
169	-1	-1	-1	1	-1	1	-1	1	-1	-1	-1	1
170	1	-1	-1	1	-1	1	-1	1	1	1	1	-1
171	-1	1	-1	1	-1	1	-1	1	1	1	1	1
172	1	1	-1	1	-1	1	-1	1	-1	-1	-1	-1
173	-1	-1	1	1	-1	1	-1	1	1	1	-1	-1
174	1	-1	1	1	-1	1	-1	1	-1	-1	1	1
175	-1	1	1	1	-1	1	-1	1	-1	-1	1	-1
176	1	1	1	1	-1	1	-1	1	1	1	-1	1
177	-1	-1	-1	-1	1	1	-1	1	-1	1	1	-1
178	1	-1	-1	-1	1	1	-1	1	1	-1	-1	1
179	-1	1	-1	-1	1	1	-1	1	1	-1	-1	-1
180	1	1	-1	-1	1	1	-1	1	-1	1	1	1
181	-1	-1	1	-1	1	1	-1	1	1	-1	1	1
182	1	-1	1	-1	1	1	-1	1	-1	1	-1	-1
183	-1	1	1	-1	1	1	-1	1	-1	1	-1	1
184	1	1	1	-1	1	1	-1	1	1	-1	1	-1
185	-1	-1	-1	1	1	1	-1	1	1	-1	1	-1
186	1	-1	-1	1	1	1	-1	1	-1	1	-1	1
187	-1	1	-1	1	1	1	-1	1	-1	1	-1	-1
188	1	1	-1	1	1	1	-1	1	1	-1	1	1
189	-1	-1	1	1	1	1	-1	1	-1	1	1	1
190	1	-1	1	1	1	1	-1	1	1	-1	-1	-1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
191	-1	1	1	1	1	1	-1	1	1	-1	-1	1
192	1	1	1	1	1	1	-1	1	-1	1	1	-1
193	-1	-1	-1	-1	-1	-1	1	1	1	1	1	-1
194	1	-1	-1	-1	-1	-1	1	1	-1	-1	-1	1
195	-1	1	-1	-1	-1	-1	1	1	-1	-1	-1	-1
196	1	1	-1	-1	-1	-1	1	1	1	1	1	1
197	-1	-1	1	-1	-1	-1	1	1	-1	-1	1	1
198	1	-1	1	-1	-1	-1	1	1	1	1	-1	-1
199	-1	1	1	-1	-1	-1	1	1	1	1	-1	1
200	1	1	1	-1	-1	-1	1	1	-1	-1	1	-1
201	-1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1
202	1	-1	-1	1	-1	-1	1	1	1	1	-1	1
203	-1	1	-1	1	-1	-1	1	1	1	1	-1	-1
204	1	1	-1	1	-1	-1	1	1	-1	-1	1	1
205	-1	-1	1	1	-1	-1	1	1	1	1	1	1
206	1	-1	1	1	-1	-1	1	1	-1	-1	-1	-1
207	-1	1	1	1	-1	-1	1	1	-1	-1	-1	1
208	1	1	1	1	-1	-1	1	1	1	1	1	-1
209	-1	-1	-1	-1	1	-1	1	1	-1	1	-1	1
210	1	-1	-1	-1	1	-1	1	1	1	-1	1	-1
211	-1	1	-1	-1	1	-1	1	1	1	-1	1	1
212	1	1	-1	-1	1	-1	1	1	-1	1	-1	-1
213	-1	-1	1	-1	1	-1	1	1	1	-1	-1	-1
214	1	-1	1	-1	1	-1	1	1	-1	1	1	1
215	-1	1	1	-1	1	-1	1	1	-1	1	1	-1
216	1	1	1	-1	1	-1	1	1	1	-1	-1	1
217	-1	-1	-1	1	1	-1	1	1	1	-1	-1	1
218	1	-1	-1	1	1	-1	1	1	-1	1	1	-1
219	-1	1	-1	1	1	-1	1	1	-1	1	1	1
220	1	1	-1	1	1	-1	1	1	1	-1	-1	-1
221	-1	-1	1	1	1	-1	1	1	-1	1	-1	-1
222	1	-1	1	1	1	-1	1	1	1	-1	1	1
223	-1	1	1	1	1	-1	1	1	1	-1	1	-1
224	1	1	1	1	1	-1	1	1	-1	1	-1	1
225	-1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1
226	1	-1	-1	-1	-1	1	1	1	1	-1	1	1
227	-1	1	-1	-1	-1	1	1	1	1	-1	1	-1
228	1	1	-1	-1	-1	1	1	1	-1	1	-1	1
229	-1	-1	1	-1	-1	1	1	1	1	-1	-1	1
230	1	-1	1	-1	-1	1	1	1	-1	1	1	-1
231	-1	1	1	-1	-1	1	1	1	-1	1	1	1
232	1	1	1	-1	-1	1	1	1	1	-1	-1	-1
233	-1	-1	-1	1	-1	1	1	1	1	-1	-1	-1
234	1	-1	-1	1	-1	1	1	1	-1	1	1	1
235	-1	1	-1	1	-1	1	1	1	-1	1	1	-1
236	1	1	-1	1	-1	1	1	1	1	-1	-1	1
237	-1	-1	1	1	-1	1	1	1	-1	1	-1	1
238	1	-1	1	1	-1	1	1	1	1	-1	1	-1
239	-1	1	1	1	-1	1	1	1	1	-1	1	1
240	1	1	1	1	-1	1	1	1	-1	1	-1	-1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
241	-1	-1	-1	-1	1	1	1	1	1	1	1	1
242	1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1
243	-1	1	-1	-1	1	1	1	1	-1	-1	-1	1
244	1	1	-1	-1	1	1	1	1	1	1	1	-1
245	-1	-1	1	-1	1	1	1	1	-1	-1	1	-1
246	1	-1	1	-1	1	1	1	1	1	1	-1	1
247	-1	1	1	-1	1	1	1	1	1	1	-1	-1
248	1	1	1	-1	1	1	1	1	-1	-1	1	1
249	-1	-1	-1	1	1	1	1	1	-1	-1	1	1
250	1	-1	-1	1	1	1	1	1	1	1	-1	-1
251	-1	1	-1	1	1	1	1	1	1	1	-1	1
252	1	1	-1	1	1	1	1	1	-1	-1	1	-1
253	-1	-1	1	1	1	1	1	1	1	1	1	-1
254	1	-1	1	1	1	1	1	1	-1	-1	-1	1
255	-1	1	1	1	1	1	1	1	-1	-1	-1	-1
256	1	1	1	1	1	1	1	1	1	1	1	1

12 Coefficients, 2 levels, 1/32 Fractional Factorial Design

GENERAL DESIGN INFORMATION

128 runs, 12 factors,
Resolution IV

Design generating information:

Generators

H=ABCDE J=ABCFG K=ABDF L=ACEG M=ADEFG

WARNING

CONFOUNDING

AH=JM AJ=HM AM=HJ

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	-1
2	1	-1	-1	-1	-1	-1	-1	1	1	-1	-1	1
3	-1	1	-1	-1	-1	-1	-1	1	1	-1	1	-1
4	1	1	-1	-1	-1	-1	-1	-1	-1	1	-1	1
5	-1	-1	1	-1	-1	-1	-1	1	1	1	-1	-1
6	1	-1	1	-1	-1	-1	-1	-1	-1	-1	1	1
7	-1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1
8	1	1	1	-1	-1	-1	-1	1	1	1	1	1
9	-1	-1	-1	1	-1	-1	-1	1	-1	-1	1	1
10	1	-1	-1	1	-1	-1	-1	-1	1	1	-1	-1
11	-1	1	-1	1	-1	-1	-1	-1	1	1	1	1
12	1	1	-1	1	-1	-1	-1	1	-1	-1	-1	-1
13	-1	-1	1	1	-1	-1	-1	-1	1	-1	-1	1
14	1	-1	1	1	-1	-1	-1	1	-1	1	1	-1
15	-1	1	1	1	-1	-1	-1	1	-1	1	-1	1
16	1	1	1	1	-1	-1	-1	-1	1	-1	1	-1
17	-1	-1	-1	-1	1	-1	-1	1	-1	1	-1	1
18	1	-1	-1	-1	1	-1	-1	-1	1	-1	1	-1
19	-1	1	-1	-1	1	-1	-1	-1	1	-1	-1	1
20	1	1	-1	-1	1	-1	-1	1	-1	1	1	-1
21	-1	-1	1	-1	1	-1	-1	-1	1	1	1	1
22	1	-1	1	-1	1	-1	-1	1	-1	-1	-1	-1
23	-1	1	1	-1	1	-1	-1	1	-1	-1	1	1
24	1	1	1	-1	1	-1	-1	-1	1	1	-1	-1
25	-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
26	1	-1	-1	1	1	-1	-1	1	1	1	1	1
27	-1	1	-1	1	1	-1	-1	1	1	1	-1	-1
28	1	1	-1	1	1	-1	-1	-1	-1	-1	1	1
29	-1	-1	1	1	1	-1	-1	1	1	-1	1	-1
30	1	-1	1	1	1	-1	-1	-1	-1	1	-1	1
31	-1	1	1	1	1	-1	-1	-1	-1	1	1	-1
32	1	1	1	1	1	-1	-1	1	1	-1	-1	1
33	-1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1
34	1	-1	-1	-1	-1	1	-1	1	-1	1	-1	-1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
35	-1	1	-1	-1	-1	1	-1	1	-1	1	1	1
36	1	1	-1	-1	-1	1	-1	-1	1	-1	-1	-1
37	-1	-1	1	-1	-1	1	-1	1	-1	-1	-1	1
38	1	-1	1	-1	-1	1	-1	-1	1	1	1	-1
39	-1	1	1	-1	-1	1	-1	-1	1	1	-1	1
40	1	1	1	-1	-1	1	-1	1	-1	-1	1	-1
41	-1	-1	-1	1	-1	1	-1	1	1	1	1	-1
42	1	-1	-1	1	-1	1	-1	-1	-1	-1	-1	1
43	-1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1
44	1	1	-1	1	-1	1	-1	1	1	1	-1	1
45	-1	-1	1	1	-1	1	-1	-1	-1	1	-1	-1
46	1	-1	1	1	-1	1	-1	1	1	-1	1	1
47	-1	1	1	1	-1	1	-1	1	1	-1	-1	-1
48	1	1	1	1	-1	1	-1	-1	-1	1	1	1
49	-1	-1	-1	-1	1	1	-1	1	1	-1	-1	-1
50	1	-1	-1	-1	1	1	-1	-1	-1	1	1	1
51	-1	1	-1	-1	1	1	-1	-1	-1	1	-1	-1
52	1	1	-1	-1	1	1	-1	1	1	-1	1	1
53	-1	-1	1	-1	1	1	-1	-1	-1	-1	1	-1
54	1	-1	1	-1	1	1	-1	1	1	1	-1	1
55	-1	1	1	-1	1	1	-1	1	1	1	1	-1
56	1	1	1	-1	1	1	-1	-1	-1	-1	-1	1
57	-1	-1	-1	1	1	1	-1	-1	1	1	-1	1
58	1	-1	-1	1	1	1	-1	1	-1	-1	1	-1
59	-1	1	-1	1	1	1	-1	1	-1	-1	-1	1
60	1	1	-1	1	1	1	-1	-1	1	1	1	-1
61	-1	-1	1	1	1	1	-1	1	-1	1	1	1
62	1	-1	1	1	1	1	-1	-1	1	-1	-1	-1
63	-1	1	1	1	1	1	-1	-1	1	-1	1	1
64	1	1	1	1	1	1	-1	1	-1	1	-1	-1
65	-1	-1	-1	-1	-1	-1	1	-1	1	1	-1	1
66	1	-1	-1	-1	-1	-1	1	1	-1	-1	1	-1
67	-1	1	-1	-1	-1	-1	1	1	-1	-1	-1	1
68	1	1	-1	-1	-1	-1	1	-1	1	1	1	-1
69	-1	-1	1	-1	-1	-1	1	1	-1	1	1	1
70	1	-1	1	-1	-1	-1	1	-1	1	-1	-1	-1
71	-1	1	1	-1	-1	-1	1	-1	1	-1	1	1
72	1	1	1	-1	-1	-1	1	1	-1	1	-1	-1
73	-1	-1	-1	1	-1	-1	1	1	1	-1	-1	-1
74	1	-1	-1	1	-1	-1	1	-1	-1	1	1	1
75	-1	1	-1	1	-1	-1	1	-1	-1	1	-1	-1
76	1	1	-1	1	-1	-1	1	1	1	-1	1	1
77	-1	-1	1	1	-1	-1	1	-1	-1	-1	1	-1
78	1	-1	1	1	-1	-1	1	1	1	1	-1	1
79	-1	1	1	1	-1	-1	1	1	1	1	1	-1
80	1	1	1	1	-1	-1	1	-1	-1	-1	-1	1
81	-1	-1	-1	-1	1	-1	1	1	1	1	1	-1
82	1	-1	-1	-1	1	-1	1	-1	-1	-1	-1	1
83	-1	1	-1	-1	1	-1	1	-1	-1	-1	1	-1
84	1	1	-1	-1	1	-1	1	1	1	1	-1	1

Design												
Run	A	B	C	D	E	F	G	H	I	J	K	L
85	-1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1
86	1	-1	1	-1	1	-1	1	1	1	-1	1	1
87	-1	1	1	-1	1	-1	1	1	1	-1	-1	-1
88	1	1	1	-1	1	-1	1	-1	-1	1	1	1
89	-1	-1	-1	1	1	-1	1	-1	1	-1	1	1
90	1	-1	-1	1	1	-1	1	1	-1	1	-1	-1
91	-1	1	-1	1	1	-1	1	1	-1	1	1	1
92	1	1	-1	1	1	-1	1	-1	1	-1	-1	-1
93	-1	-1	1	1	1	-1	1	1	-1	-1	-1	1
94	1	-1	1	1	1	-1	1	-1	1	1	1	-1
95	-1	1	1	1	1	-1	1	-1	1	1	-1	1
96	1	1	1	1	1	-1	1	1	-1	-1	1	-1
97	-1	-1	-1	-1	-1	1	1	-1	-1	-1	-1	-1
98	1	-1	-1	-1	-1	1	1	1	1	1	1	1
99	-1	1	-1	-1	-1	1	1	1	1	1	-1	-1
100	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1
101	-1	-1	1	-1	-1	1	1	1	1	-1	1	-1
102	1	-1	1	-1	-1	1	1	-1	-1	1	-1	1
103	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1
104	1	1	1	-1	-1	1	1	1	1	-1	-1	1
105	-1	-1	-1	1	-1	1	1	1	-1	1	-1	1
106	1	-1	-1	1	-1	1	1	-1	1	-1	1	-1
107	-1	1	-1	1	-1	1	1	-1	1	-1	-1	1
108	1	1	-1	1	-1	1	1	1	-1	1	1	-1
109	-1	-1	1	1	-1	1	1	-1	1	1	1	1
110	1	-1	1	1	-1	1	1	1	-1	-1	-1	-1
111	-1	1	1	1	-1	1	1	1	-1	-1	1	1
112	1	1	1	1	-1	1	1	-1	1	1	-1	-1
113	-1	-1	-1	-1	1	1	1	1	-1	-1	1	1
114	1	-1	-1	-1	1	1	1	-1	1	1	-1	-1
115	-1	1	-1	-1	1	1	1	-1	1	1	1	1
116	1	1	-1	-1	1	1	1	1	-1	-1	-1	-1
117	-1	-1	1	-1	1	1	1	-1	1	-1	-1	1
118	1	-1	1	-1	1	1	1	1	-1	1	1	-1
119	-1	1	1	-1	1	1	1	1	-1	1	-1	1
120	1	1	1	-1	1	1	1	-1	1	-1	1	-1
121	-1	-1	-1	1	1	1	1	-1	-1	1	1	-1
122	1	-1	-1	1	1	1	1	1	1	-1	-1	1
123	-1	1	-1	1	1	1	1	1	1	-1	1	-1
124	1	1	-1	1	1	1	1	-1	-1	1	-1	1
125	-1	-1	1	1	1	1	1	1	1	1	-1	-1
126	1	-1	1	1	1	1	1	-1	-1	-1	1	1
127	-1	1	1	1	1	1	1	-1	-1	-1	-1	-1
128	1	1	1	1	1	1	1	1	1	1	1	1

D: SIGINI Fortran Code for Stress Mapping

The SIGINI code is needed for stress mapping, it reads some important information about the nodes and elements analyzed and gives a response, some values for stress in 6 variables, for example, in three-dimensional continuum elements six stress components must be defined in the order $\sigma_1, \sigma_2, \sigma_3, \sigma_12, \sigma_13, \sigma_23$. The developed script defines σ_1 and σ_2 only, L and LT direction residual stresses. It takes the position of each node to map a residual stress value for defined directions. The `sigini_input.txt` file generated from each simulation contains important information for the simulation analysis, the residual stress coefficients from L and LT direction, the thickness of the plate and the affine transformation matrix of position. The SIGINI file reads all these information for residual stress output.

SIGINI Code

```

c-----+-----+-----+-----+-----+-----+-----+
c-----2-----3-----4-----5-----6-----7-----8
c-----+-----+-----+-----+-----+-----+-----+
c
SUBROUTINE SIGINI(SIGMA,COORDS,NTENS,NCRDS,NOEL,NPT,LAYER,
+ KSPT,LREBAR,REBARN)
parameter (Nmax=2000000)
real*8 sigma(*),coords(*)
real*8 XU(Nmax),YU1(Nmax),YU2(Nmax),Y21(Nmax),Y22(Nmax)
real*8 XA,YA1,YA2
real*8 H3(6,43000),H1(3,43000),H2(3,43000)
real*8 COS1,COS2,COS3
real*8 GAUSS(21),TH(40000)
INTEGER INITIAL,MAXNUM,N,PRINTFLAG,OLDELM,i1,i2
REAL*8 ZOffset
CHARACTER*80 REBARN
CHARACTER*250 REFSURFFILE,REFSURFFILE1,REFSURFFILE2,REFSURFFILE3
SAVE H1,H2,H3,TH,INITIAL,Y21,Y22,N,XU,YU1,YU2,ZOffset,PRINTFLAG,
+ OLDELM,r1c1,r1c2,r1c3,r1c4,r2c1,r2c2,r2c3,r2c4,r3c1,r3c2
+ r3c3,r3c4,r4c1,r4c2,r4c3,r4c4
DATA GAUSS/ -1.0,-0.9,-0.8,-0.7,-0.6,-0.5,-0.4,-0.3,-0.2,-0.1,
+ 0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0/
c
c Added statements for dealing with prescribed Residual Stress coefficients :
LOGICAL boolExist1,boolExist2,boolExist3,boolExist4
LOGICAL boolGObbranch1,boolGObbranch2,boolGObbranch3
CHARACTER*80 line
real*8 RS_L_c1,RS_L_c2,RS_L_c3,RS_L_c4,RS_L_c5,RS_L_c6
real*8 RS_LT_c1,RS_LT_c2,RS_LT_c3
real*8 RS_LT_c4,RS_LT_c5,RS_LT_c6
real*8 r1c1,r1c2,r1c3,r1c4,r2c1,r2c2,r2c3,r2c4,r3c1,r3c2
real*8 r3c3,r3c4,r4c1,r4c2,r4c3,r4c4
real*8 BilletThickness,Zad
real*8 aux0,aux1,aux2,aux3,aux4,aux5,aux6,C1,C2,C3
Statements executed only the first time *SIGINI* is called :

```

```

IF(INITIAL.EQ.0) THEN
c
path= "./"
filename = "sigini_output.txt" ! for storing the results
i1 = index(path,' ') - 1
i2= index(filename,' ') - 1
len_path = LENGTH(path)
len_filename = LENGTH(filename)
write(*,*)
c write(*,*) "verif : len_path=",len_path," since i1=",i1
c write(*,*) "verif : len_filename=",len_filename," since i2=",i2
path2filename1 = path(1:i1)//filename(1:i2) ! concatenation without added blank
write(*,*) "Sigini.f results stored in: ",path2filename1
write(*,*)
OPEN(16,FILE=path2filename1,ERR=304) ! file which will stored the results
c INFO : the closure of that file will be not done into *SIGINI*
c INFO : as far as this subroutine is called within a loop over NOEL !
c
PRINTFLAG=0
OLDELM=0
c
boolGObbranch1 = .False.
boolGObbranch2 = .False.
boolGObbranch3 = .False.
boolExist1 = .False.
boolExist2 = .False.
boolExist3 = .False.
boolExist4 = .False.
BilletThickness = 0.0
filename = "sigini_input.txt"
INQUIRE(FILE=filename,EXIST=boolExist1)
IF (boolExist1) THEN
c -----
WRITE(*,*)
WRITE(*,*) "A sigini_input-file has been found"
WRITE(*,*)
OPEN(12,FILE=filename,STATUS='OLD')
c We skip the reading of the working directory and assume it will always
c be the current directory ccx is executed
c 2/ read the billet Thickness :
IF (line .ne. "") THEN
READ(12,*) BilletThickness
WRITE(*,*) "BilletThickness found: ",BilletThickness
WRITE(*,*)
ENDIF
c 3/ Read two sets of six coefficients,
c one set for the Rolling Direction (L) Residual Stresses,
c one set for the CrossRolling Direction (LT) Residual Stresses :

```

```

IF (line .ne. "") THEN
READ(12,*) RS_L_c1, RS_L_c2, RS_L_c3, RS_L_c4, RS_L_c5, RS_L_c6
READ(12,*) RS_LT_c1, RS_LT_c2, RS_LT_c3, RS_LT_c4, RS_LT_c5,
1 RS_LT_c6
WRITE(*,*) "L stress coeffs found:"
WRITE(*,*) RS_L_c1, RS_L_c2, RS_L_c3, RS_L_c4, RS_L_c5, RS_L_c6
WRITE(*,*)
WRITE(*,*) "LT stress coeffs found:"
WRITE(*,*) RS_LT_c1, RS_LT_c2, RS_LT_c3, RS_LT_c4, RS_LT_c5,
1 RS_LT_c6
WRITE(*,*)
ENDIF
c 3/1 - Read the transformation matrix
IF (line .ne. "") THEN
READ(12,*) r1c1,r1c2,r1c3,r1c4,r2c1,r2c2,r2c3,r2c4,r3c1,r3c2,
1 r3c3,r3c4,r4c1,r4c2,r4c3,r4c4
WRITE(*,*) "Matrix coeffs 1-2 found:"
WRITE(*,*) r1c1,r1c2,r1c3,r1c4,r2c1,r2c2,r2c3,r2c4
WRITE(*,*)
WRITE(*,*) "Matrix coeffs 3-4 found:"
WRITE(*,*) r3c1,r3c2,r3c3,r3c4,r4c1,r4c2,r4c3,r4c4
WRITE(*,*)
ENDIF
c 4/ Read the number of elements :
c The number of elements is not important for the version at Toulouse
c therefore we can set it to a fake number
NN = 5000
ZOffset = 0
CLOSE(12)
boolGObbranch3 = .True.
write(*,*)
write(*,*) "No need to read shell thicknesses (solids only)"
write(*,*) "No need to read raw residual stresses"
write(*,*) "No use of matrix coeffs H1 and H2"
write(*,*)
ELSE ! boolExist1 = .false.
c -----
WRITE(*,*)
WRITE(*,*) "No sigini_input.txt found !"
path= "./"
write(*,*)
write(*,*) "Error in sigini.f, working dir=",path
write(*,*)
c *****
c START OF MAIN CODE
c Code below executes each time subroutine is called
c
IF ( boolGObbranch3 ) THEN

```

```

C1=r1c1*COORDS(1)+r1c2*COORDS(2)+r1c3*COORDS(3)+r1c4
C2=r2c1*COORDS(1)+r2c2*COORDS(2)+r2c3*COORDS(3)+r2c4
C3=r3c1*COORDS(1)+r3c2*COORDS(2)+r3c3*COORDS(3)+r3c4
Y=C3
if (NOEL.le.3) then
write(*,*) "verif for ELEMENT=",NOEL," : Y=",Y," with "
write(*,*) "COORDS(3)=",COORDS(3)," ZOffset=",ZOffset
write(*,*)
endif
Zad = Y / BilletThickness
aux0 = 2*3.1415927*Zad
c Presuming billet to be alligned with world coords, L-dir = X and LT = Y
c One would expect S1==Sx and S2==Sy, but test shows inverse, so:
aux1 = RS_L_c1
aux2 = RS_L_c2*COS( aux0)
aux3 = RS_L_c3*COS(2*aux0)
aux4 = RS_L_c4*COS(3*aux0)
aux5 = RS_L_c5*COS(4*aux0)
aux6 = RS_L_c6*COS(5*aux0)
SIGMA(1)=aux1+aux2+aux3+aux4+aux5+aux6
aux1 = RS_LT_c1
aux2 = RS_LT_c2*COS( aux0)
aux3 = RS_LT_c3*COS(2*aux0)
aux4 = RS_LT_c4*COS(3*aux0)
aux5 = RS_LT_c5*COS(4*aux0)
aux6 = RS_LT_c6*COS(5*aux0)
SIGMA(2)=aux1+aux2+aux3+aux4+aux5+aux6
SIGMA(3)=0.0
SIGMA(4)=0.0
SIGMA(5)=0.0
SIGMA(6)=0.0
YY11 = SIGMA(1)
YY22 = SIGMA(2)
YY33 = 0.0

```

E: CalculiX GraphiX (cgx) Case Study Results

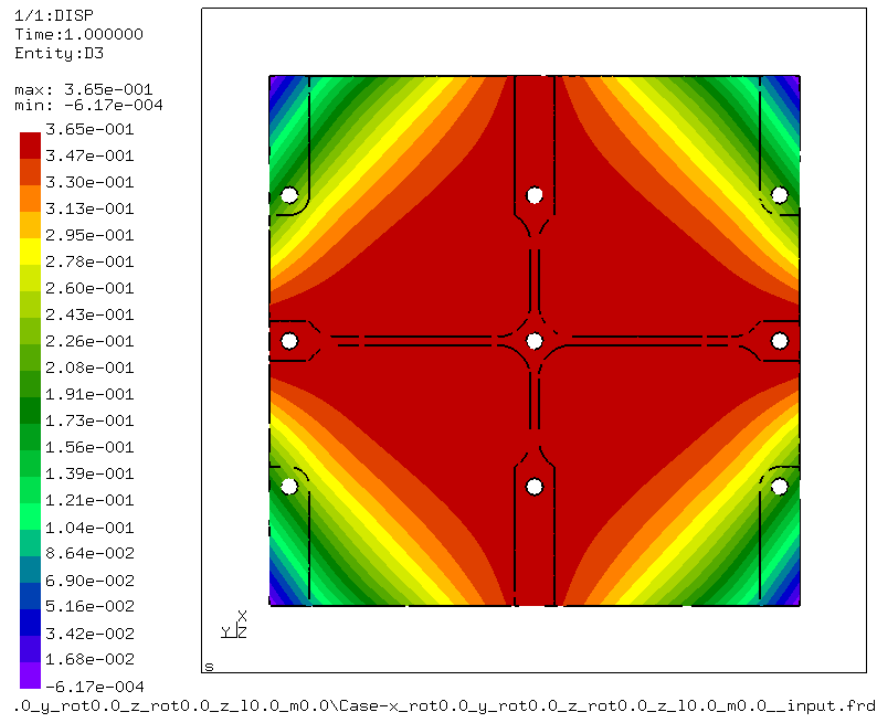


Figure 123: Cgxr result (distortion in Z direction) for 0 mm Z offset.

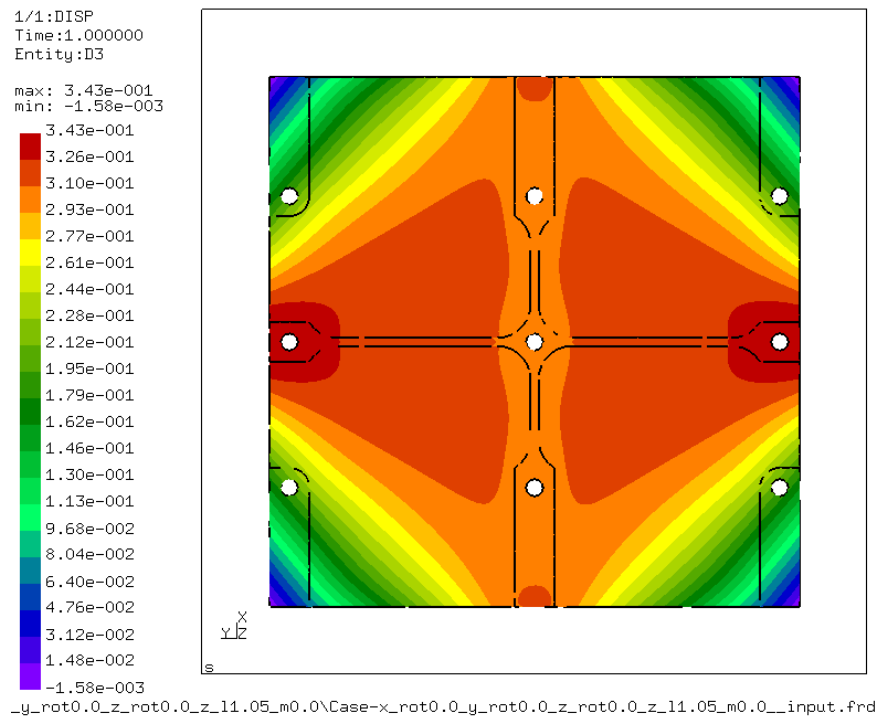


Figure 124: Cgxr result (distortion in Z direction) for 1.05 mm Z offset.

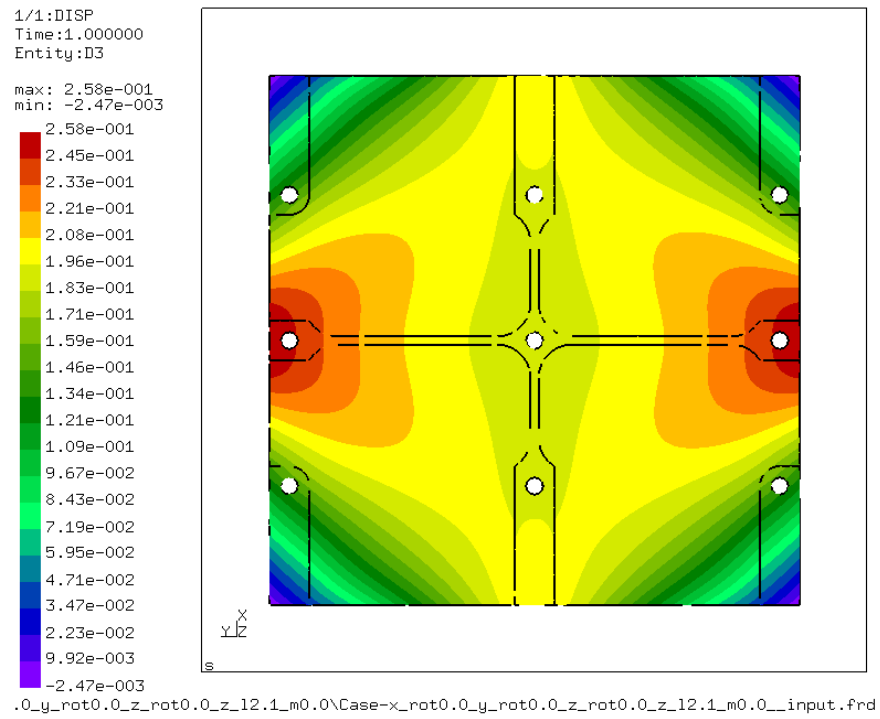


Figure 125: Cgx result (distortion in Z direction) for 2.1 mm Z offset.

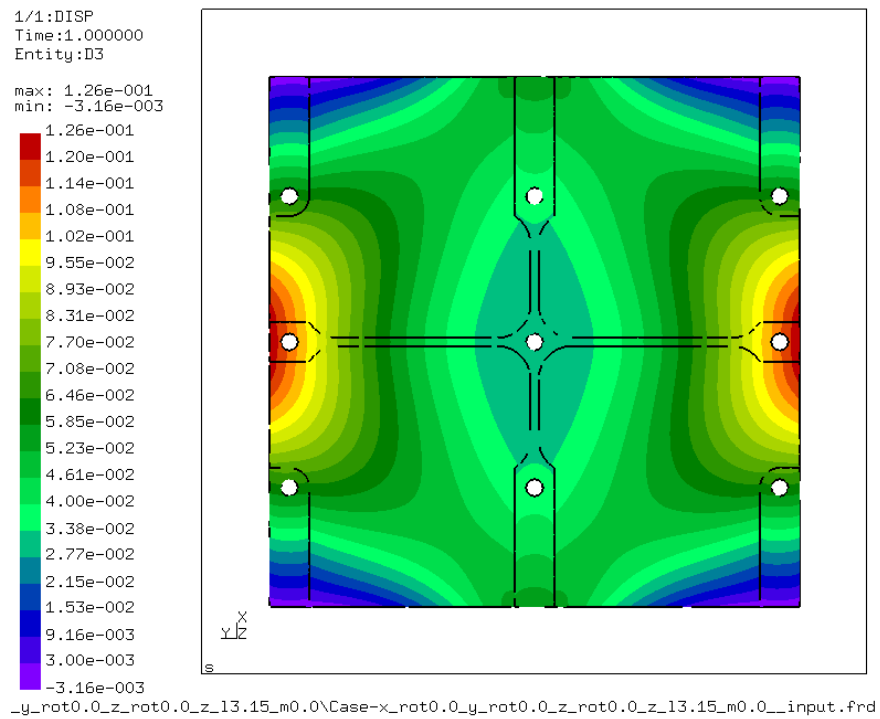


Figure 126: Cgx result (distortion in Z direction) for 3.15 mm Z offset.

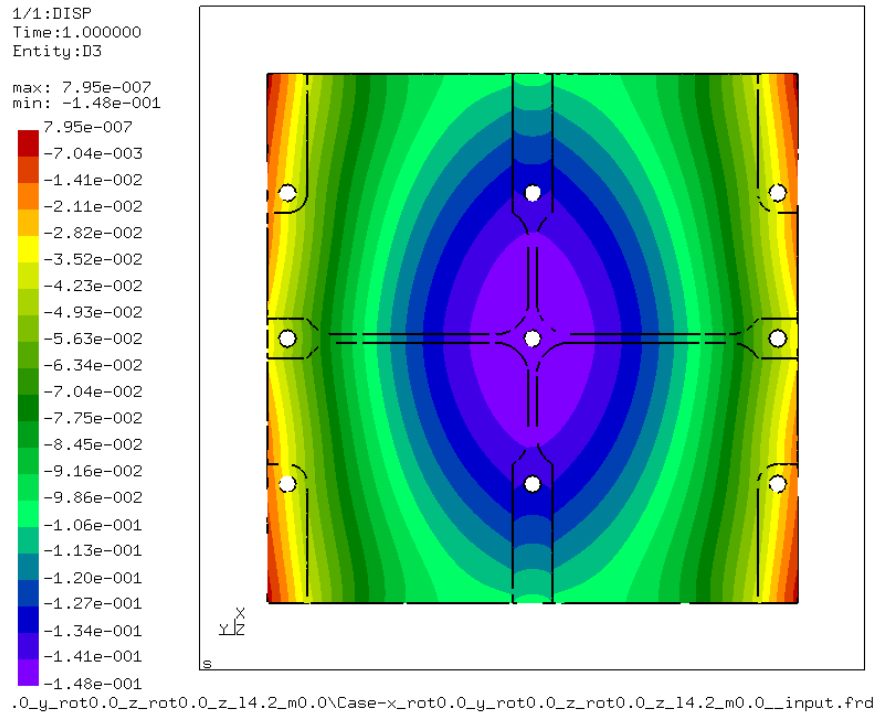


Figure 127: Cgx result (distortion in Z direction) for 4.2 mm Z offset.

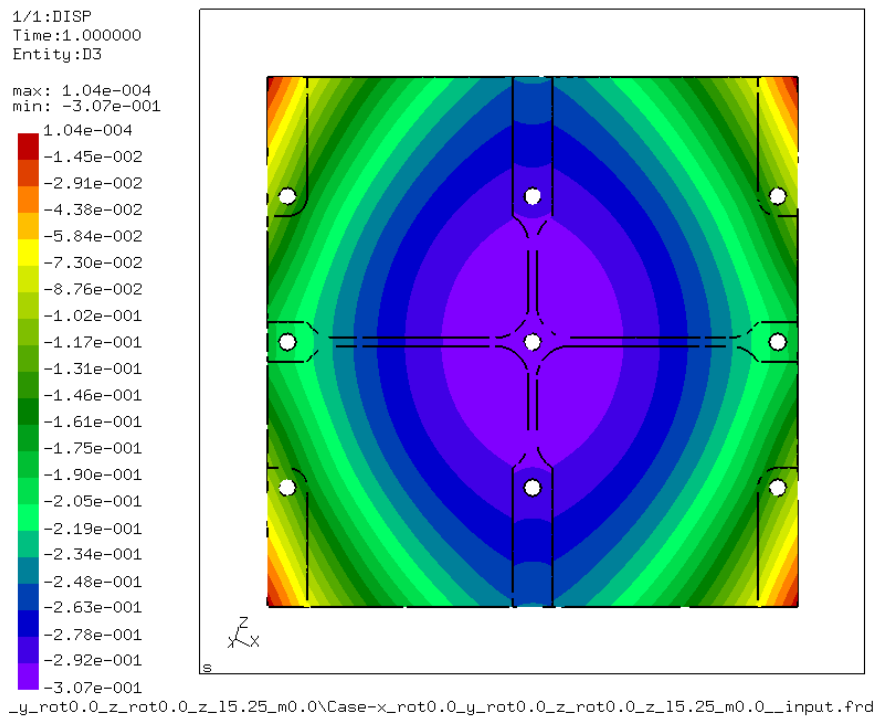


Figure 128: Cgx result (distortion in Z direction) for 5.25 mm Z offset.

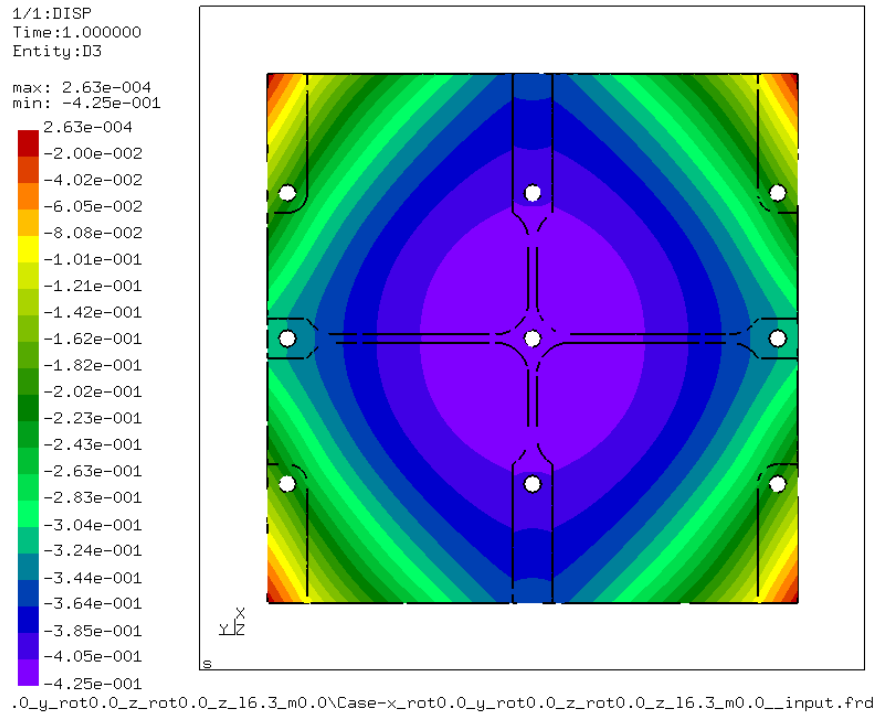


Figure 129: Cgx result (distortion in Z direction) for 6.3 mm Z offset.

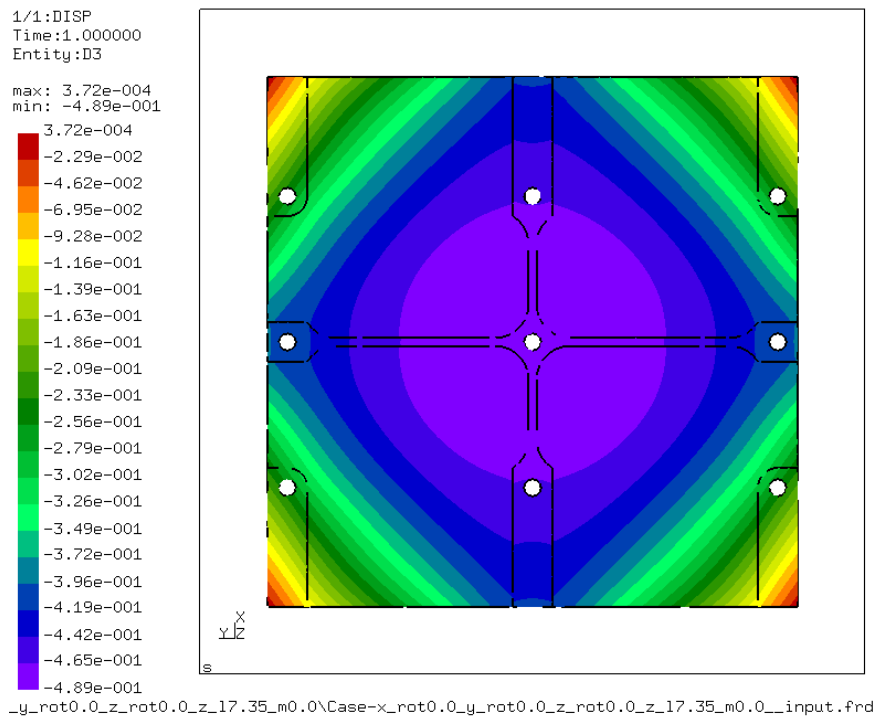


Figure 130: Cgx result (distortion in Z direction) for 7.35 mm Z offset.

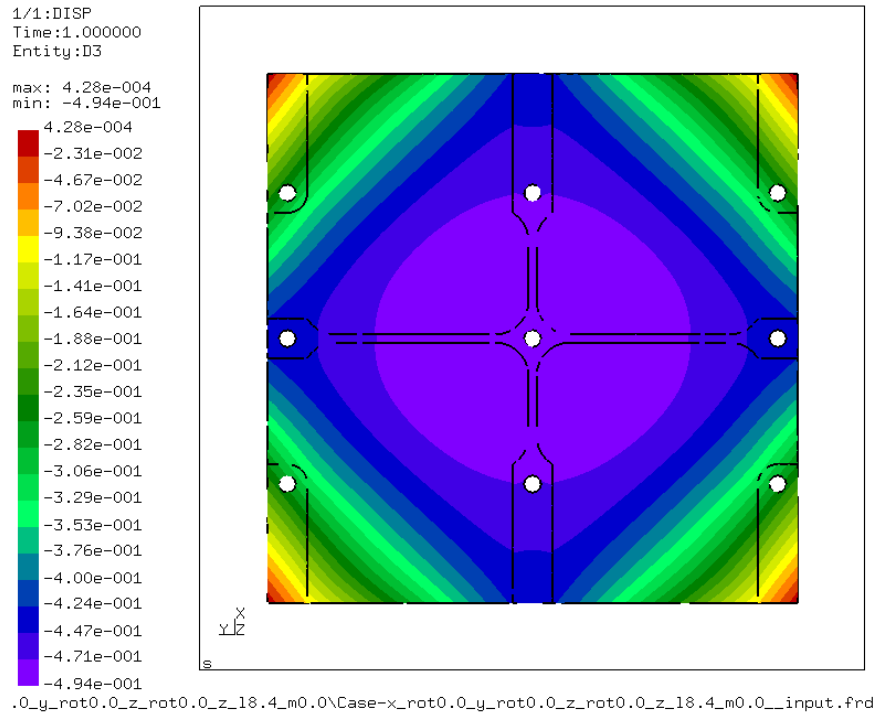


Figure 131: Cgx result (distortion in Z direction) for 8.4 mm Z offset.

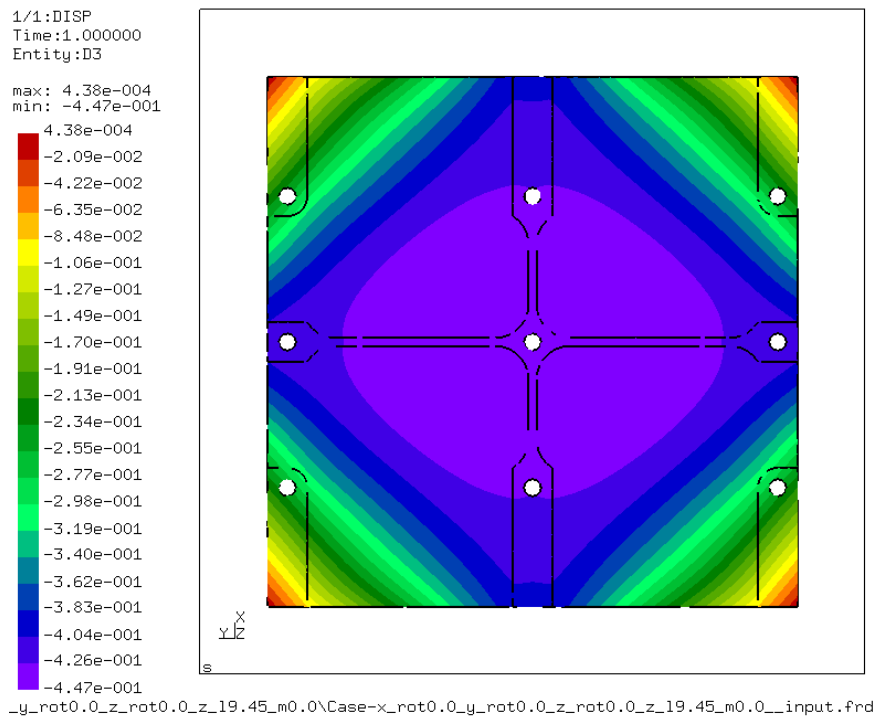


Figure 132: Cgx result (distortion in Z direction) for 9.45 mm Z offset.

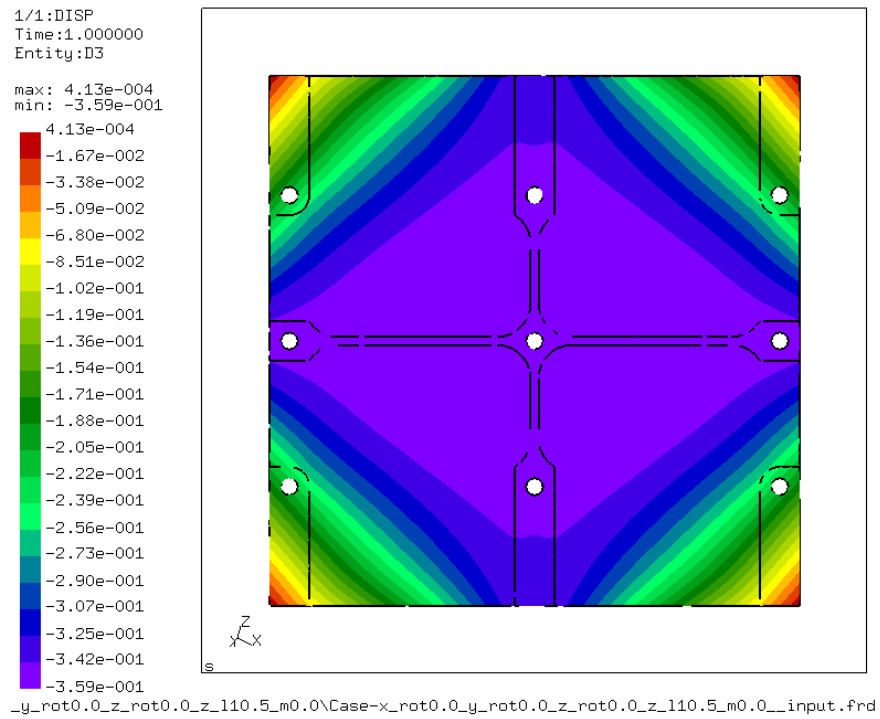


Figure 133: Cgx result (distortion in Z direction) for 10.5 mm Z offset.

F: Output .cvs Format Table of Case Study Results

Result Table of the Positioning of the Part into the Case Study

This table is generated into a .cvs format file when running FreeCAD **Read results** section into the **Part Distortion** module. The output files after CalculiX solving process are read and concentrated into a table where the name of the file, variables (rotation about x, rotation about y, rotation about z, z offset and general material variation) and results (minimal and maximal distortion in x, y and z). This table is resumed from the case study [z offset going from 0 mm to 10.5 mm every 1.05 mm].

RotX	RotY	RotZ	TransZ	MatVar	XMin	XMax	YMin	YMax	ZMin	ZMax	LMin	LMax
0	0	0	0	0	-0.0782011	0.0695454	-0.105512	0.111033	-0.000617335	0.36488	0	0.364973822
0	0	0	1.05	0	-0.0739646	0.0715041	-0.0876016	0.108102	-0.0015782	0.342645	0	0.343276353
0	0	0	2.1	0	-0.0561635	0.0623911	-0.0496379	0.0862946	-0.00247121	0.25777	0	0.260388309
0	0	0	3.15	0	-0.0283844	0.0442979	-0.000718111	0.0512121	-0.00316387	0.126276	0	0.135717071
0	0	0	4.2	0	-0.00376551	0.0286425	0	0.0593353	-0.147915	7.95E-07	0	0.151365417
0	0	0	5.25	0	-0.0113943	0.0425654	-0.0348318	0.0963568	-0.306891	0.00010426	0	0.30881466
0	0	0	6.3	0	-0.044707	0.0660757	-0.0616147	0.128325	-0.419909	0.000344952	0	0.42128089
0	0	0	7.35	0	-0.0605661	0.091512	-0.0851967	0.133042	-0.488676	0.000371766	0	0.489498818
0	0	0	8.4	0	-0.0755305	0.0994347	-0.0936453	0.128478	-0.494156	0.00042792	0	0.494609551
0	0	0	9.45	0	-0.0814011	0.0946915	-0.0927252	0.113024	-0.446951	0.000438178	0	0.447124106
0	0	0	10.5	0	-0.0780439	0.0787514	-0.0849787	0.0908395	-0.358765	0.000412558	0	0.35879205

Result Table of the 12 Coefficients Variation, 2 levels, 1/16 Fractional Factorial Design for the Case Study

This table is generated into a .csv format file when running FreeCAD **Read results** section into the **Part Distortion** module. The output files after CalculiX solving process are read and concentrated into a table where the name of the file, variables (rotation about x, rotation about y, rotation about z, z offset and combination of material variation) and results (minimal and maximal distortion in x, y and z). This table is resumed from the case study [$\pm 10\%$ variation in all coefficients into the optimal position, 3.15 mm z offset].

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-0.138913	0.00347697	0	0.149148707
3.15	10	-10	-10	-10	-10	-10	-10	-10	10	10	10	10	-0.000310947	0.152405	0	0.154486285
3.15	-10	10	-10	-10	-10	-10	-10	-10	10	10	10	-10	-0.136092	0.221287	0	0.221882604
3.15	10	10	-10	-10	-10	-10	-10	-10	-10	-10	-10	10	-0.353264	0.00174476	0	0.358326723
3.15	-10	-10	10	-10	-10	-10	-10	-10	10	10	-10	10	-0.027621	0.227631	0	0.228721451
3.15	10	-10	10	-10	-10	-10	-10	-10	-10	-10	10	-10	-0.0947128	0.00309835	0	0.10142488
3.15	-10	10	10	-10	-10	-10	-10	-10	-10	-10	10	10	-0.308814	0.00131894	0	0.311542655
3.15	10	10	10	-10	-10	-10	-10	-10	10	10	-10	-10	-0.0994959	0.277998	0	0.278797629
3.15	-10	-10	-10	10	-10	-10	-10	-10	10	10	10	-10	-0.000558703	0.443183	0	0.443723846
3.15	10	-10	-10	10	-10	-10	-10	-10	-10	-10	10	10	-0.0487007	0.0651298	0	0.10014325
3.15	-10	10	-10	10	-10	-10	-10	-10	10	10	-10	-10	-0.135755	0.102937	0	0.15451501
3.15	10	10	-10	10	-10	-10	-10	-10	-10	-10	-10	10	-0.00315139	0.38232	0	0.385747689
3.15	-10	-10	10	-10	-10	-10	-10	-10	10	10	-10	-10	-0.0150344	0.147474	0	0.151865422
3.15	10	-10	10	10	-10	-10	-10	-10	-10	10	10	-10	-0.000767031	0.439372	0	0.439576015
3.15	-10	10	10	10	-10	-10	-10	-10	10	-10	-10	10	-0.00254643	0.350082	0	0.352714014
3.15	10	10	10	10	-10	-10	-10	-10	-10	-10	-10	-10	-0.0876438	0.184045	0	0.198367002
3.15	-10	-10	-10	-10	10	-10	-10	-10	10	-10	10	10	-0.126708	0.00303793	0	0.131442897
3.15	10	-10	-10	-10	10	-10	-10	-10	-10	10	-10	-10	-0.0143265	0.155697	0	0.161808967
3.15	-10	10	-10	-10	10	-10	-10	-10	-10	10	-10	10	-0.186459	0.126381	0	0.188416597
3.15	10	10	-10	-10	10	-10	-10	-10	10	-10	10	-10	-0.283026	0.0528612	0	0.288038298
3.15	-10	-10	10	-10	10	-10	-10	-10	-10	10	10	-10	-0.000243856	0.149974	0	0.151473563
3.15	10	-10	10	-10	10	-10	-10	-10	10	-10	-10	10	-0.0786004	0.0398142	0	0.095196992
3.15	-10	10	10	-10	10	-10	-10	-10	-10	-10	-10	-10	-0.234927	0.0982176	0	0.246014624
3.15	10	10	10	-10	10	-10	-10	-10	-10	10	10	10	-0.141525	0.0898673	0	0.141662587
3.15	-10	-10	-10	10	10	-10	-10	-10	-10	10	10	-10	-0.000402572	0.247452	0	0.247551596
3.15	10	-10	-10	10	10	-10	-10	-10	10	-10	-10	-10	-1.56E-06	0.250052	0	0.253754631
3.15	-10	10	-10	10	10	-10	-10	-10	-10	-10	-10	10	-0.119836	0.199717	0	0.213806049
3.15	10	10	-10	10	10	-10	-10	-10	-10	10	10	-10	-0.00707844	0.2858	0	0.289790244
3.15	-10	-10	10	10	10	-10	-10	-10	10	-10	-10	-10	-1.21E-06	0.242902	0	0.24497982

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	10	-10	10	10	10	-10	-10	-10	-10	10	-10	10	-0.000280617	0.331377	0	0.33178879
3.15	-10	10	10	10	10	-10	-10	-10	-10	10	-10	-10	-0.0022051	0.366521	0	0.370368208
3.15	10	10	10	10	10	-10	-10	-10	10	-10	10	10	-0.0753863	0.166898	0	0.180024481
3.15	-10	-10	-10	-10	-10	10	-10	-10	10	-10	10	-10	-0.0773911	0.0300801	0	0.088004302
3.15	10	-10	-10	-10	-10	10	-10	-10	-10	10	-10	10	-0.00780349	0.116056	0	0.118041758
3.15	-10	10	-10	-10	-10	10	-10	-10	-10	10	-10	-10	-0.151428	0.179153	0	0.180497505
3.15	10	10	-10	-10	-10	10	-10	-10	10	-10	10	10	-0.290965	0.0113698	0	0.294376661
3.15	-10	-10	10	-10	-10	10	-10	-10	-10	10	10	-10	-0.000133642	0.11282	0	0.115148166
3.15	10	-10	10	-10	-10	10	-10	-10	10	-10	-10	-10	-0.032018	0.111496	0	0.116130835
3.15	-10	10	10	-10	-10	10	-10	-10	-10	-10	-10	10	-0.242862	0.0475722	0	0.251385065
3.15	10	10	10	-10	-10	10	-10	-10	-10	10	10	-10	-0.107628	0.141714	0	0.142310261
3.15	-10	-10	-10	10	-10	10	-10	-10	-10	10	10	-10	-0.000424602	0.319122	0	0.319291148
3.15	10	-10	-10	10	-10	10	-10	-10	10	-10	-10	10	-1.40E-06	0.208956	0	0.212234079
3.15	-10	10	-10	10	-10	10	-10	-10	10	-10	-10	-10	-0.0697987	0.267189	0	0.277073955
3.15	10	10	-10	10	-10	10	-10	-10	-10	10	10	10	-0.00916012	0.229509	0	0.233476263
3.15	-10	-10	10	10	-10	10	-10	-10	10	-10	10	-10	-1.06E-06	0.205701	0	0.207632723
3.15	10	-10	10	10	-10	10	-10	-10	-10	10	-10	-10	-0.000381358	0.403063	0	0.403545963
3.15	-10	10	10	10	-10	10	-10	-10	-10	10	-10	10	-0.419328	0.317237	0	0.433870052
3.15	10	10	10	10	-10	10	-10	-10	10	-10	-10	-10	-0.0253377	0.234319	0	0.243161354
3.15	-10	-10	-10	-10	10	10	-10	-10	-10	10	-10	10	-0.163402	0.00350232	0	0.170310834
3.15	10	-10	-10	-10	10	10	-10	-10	10	-10	10	-10	-0.000430225	0.2117	0	0.213131495
3.15	-10	10	-10	-10	10	10	-10	-10	10	10	10	10	-0.144929	0.170548	0	0.171068917
3.15	10	10	-10	-10	10	10	-10	-10	-10	-10	-10	-10	-0.319993	0.0181378	0	0.327125815
3.15	-10	-10	10	-10	-10	10	-10	-10	10	-10	-10	-10	-0.000445195	0.295582	0	0.2966064
3.15	10	-10	10	-10	10	10	-10	-10	-10	10	10	10	-0.149859	0.0031237	0	0.15286519
3.15	-10	10	10	-10	10	10	-10	-10	-10	-10	-10	-10	-0.275503	0.00119922	0	0.279938602
3.15	10	10	10	-10	10	10	-10	-10	10	10	-10	10	-0.106947	0.224592	0	0.225198454
3.15	-10	-10	-10	10	10	10	-10	-10	10	-10	-10	10	-0.000449483	0.393033	0	0.393472227
3.15	10	-10	-10	10	10	10	-10	-10	-10	-10	10	-10	-0.00792977	0.122635	0	0.126220977
3.15	-10	10	-10	10	10	10	-10	-10	-10	-10	10	10	-0.160422	0.0478293	0	0.174534354
3.15	10	10	-10	10	10	10	-10	-10	10	10	-10	-10	-0.00224035	0.449673	0	0.452650311
3.15	-10	-10	10	10	10	10	-10	-10	-10	-10	-10	-10	-1.48E-06	0.206567	0	0.21031881
3.15	10	-10	10	10	10	10	-10	-10	10	10	10	10	-0.000741681	0.389612	0	0.38974533
3.15	-10	10	10	10	10	10	-10	-10	-10	10	10	-10	-0.00208334	0.417012	0	0.419548584
3.15	10	10	10	10	10	10	-10	-10	-10	-10	-10	10	-0.112311	0.128816	0	0.148795638
3.15	-10	-10	-10	-10	-10	-10	10	-10	10	-10	-10	10	-0.116658	0.0223629	0	0.127813107
3.15	10	-10	-10	-10	-10	-10	10	-10	-10	10	10	-10	-0.0140528	0.11104	0	0.115776276
3.15	-10	10	-10	-10	-10	-10	10	-10	-10	10	10	10	-0.177826	0.0853088	0	0.177844374
3.15	10	10	-10	-10	-10	-10	10	-10	10	-10	-10	-10	-0.272904	0.0918543	0	0.28196913
3.15	-10	-10	10	-10	-10	-10	10	-10	-10	10	-10	-10	-0.000267701	0.19986	0	0.201145383

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	10	-10	10	-10	-10	-10	10	-10	10	-10	10	10	-0.0720664	0.00295313	0	0.080404247
3.15	-10	10	10	-10	-10	-10	10	-10	10	-10	10	-10	-0.228387	0.0548773	0	0.23441155
3.15	10	10	10	-10	-10	-10	10	-10	-10	10	-10	10	-0.135738	0.131351	0	0.145632936
3.15	-10	-10	-10	10	-10	-10	10	-10	-10	10	-10	10	-0.000271989	0.297327	0	0.297748831
3.15	10	-10	-10	10	-10	-10	10	-10	10	-10	10	-10	-1.17E-06	0.208835	0	0.211080813
3.15	-10	10	-10	10	-10	-10	10	-10	10	-10	10	10	-0.113249	0.14284	0	0.157638145
3.15	10	10	-10	10	-10	-10	10	-10	-10	10	-10	-10	-0.00589015	0.342469	0	0.346284632
3.15	-10	-10	10	10	-10	-10	10	-10	10	-10	-10	-10	-1.56E-06	0.292771	0	0.295586822
3.15	10	-10	10	10	-10	-10	10	-10	-10	10	10	10	-0.000487375	0.294095	0	0.294194393
3.15	-10	10	10	10	-10	-10	10	-10	-10	10	10	-10	-0.00241185	0.309965	0	0.313163401
3.15	10	10	10	10	-10	-10	10	-10	10	-10	-10	10	-0.0651382	0.223896	0	0.235164417
3.15	-10	-10	-10	-10	10	-10	10	-10	-10	-10	10	-10	-0.149074	0.00317251	0	0.153397148
3.15	10	-10	-10	-10	10	-10	10	-10	10	10	-10	10	-0.00594756	0.191373	0	0.196820597
3.15	-10	10	-10	-10	10	-10	10	-10	10	10	-10	-10	-0.145883	0.26819	0	0.269179413
3.15	10	10	-10	-10	10	-10	10	-10	-10	-10	10	10	-0.363421	0.0014403	0	0.365805014
3.15	-10	-10	10	-10	10	-10	10	-10	10	10	10	10	-0.000302063	0.186432	0	0.187760233
3.15	10	-10	10	-10	10	-10	10	-10	-10	-10	-10	-10	-0.100869	0.0038256	0	0.115145324
3.15	-10	10	-10	-10	10	-10	10	-10	-10	-10	-10	10	-0.315336	0.00151506	0	0.321369309
3.15	10	10	10	-10	10	-10	10	-10	10	10	10	-10	-0.103236	0.230604	0	0.231013136
3.15	-10	-10	-10	10	-10	-10	10	-10	10	10	10	-10	-0.000692863	0.392948	0	0.393154847
3.15	10	-10	-10	10	-10	-10	10	-10	-10	-10	-10	10	-0.0148907	0.100844	0	0.107243266
3.15	-10	10	-10	10	-10	-10	10	-10	-10	-10	-10	-10	-0.142343	0.159865	0	0.178027217
3.15	10	10	-10	10	-10	-10	10	-10	10	10	10	10	-0.00373727	0.325925	0	0.329169262
3.15	-10	-10	10	10	-10	-10	10	-10	-10	-10	-10	10	-0.0461797	0.098208	0	0.123240185
3.15	10	-10	10	10	-10	-10	10	-10	10	10	-10	-10	-0.000570908	0.476906	0	0.477431013
3.15	-10	10	10	10	-10	-10	10	-10	-10	-10	-10	10	-0.00235031	0.406371	0	0.40983064
3.15	10	-10	-10	-10	10	-10	10	-10	-10	-10	10	10	-0.0978935	0.126995	0	0.144682921
3.15	-10	-10	-10	-10	10	-10	10	-10	-10	-10	10	10	-0.173803	0.00329556	0	0.176293798
3.15	10	-10	-10	-10	10	-10	10	-10	10	10	-10	-10	-0.000454069	0.262017	0	0.263387627
3.15	-10	10	-10	-10	10	-10	10	-10	10	10	-10	10	-0.140341	0.214611	0	0.215320078
3.15	10	10	-10	-10	10	-10	10	-10	-10	-10	10	-10	-0.313463	0.00141827	0	0.316975142
3.15	-10	-10	10	-10	10	-10	10	-10	10	10	10	-10	-0.000420348	0.258098	0	0.259247148
3.15	10	-10	10	-10	10	-10	10	-10	-10	-10	-10	10	-0.10876	0.00341751	0	0.118915366
3.15	-10	10	10	-10	-10	-10	10	-10	-10	-10	-10	-10	-0.265356	0.0182136	0	0.273756222
3.15	10	10	10	-10	-10	-10	10	-10	10	10	10	10	-0.0972565	0.177213	0	0.177765315
3.15	-10	-10	-10	10	-10	-10	10	-10	-10	10	10	10	-0.000569819	0.355559	0	0.355689163
3.15	10	-10	-10	10	-10	-10	10	-10	-10	-10	-10	-10	-1.45E-06	0.172526	0	0.176766186
3.15	-10	10	-10	10	-10	-10	10	-10	-10	-10	-10	10	-0.150174	0.104757	0	0.172654641
3.15	10	10	-10	10	-10	-10	10	-10	10	10	10	10	-0.0024471	0.393045	0	0.395514765
3.15	-10	-10	10	10	-10	-10	10	-10	-10	-10	10	-10	-0.00824769	0.169263	0	0.171854038

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	10	-10	10	10	-10	10	10	-10	10	10	-10	10	-0.000447864	0.43948	0	0.439875209
3.15	-10	10	10	10	-10	10	10	-10	10	10	-10	-10	-0.00237234	0.473843	0	0.47629162
3.15	10	10	10	10	-10	10	10	-10	-10	-10	10	10	-0.105725	0.0719959	0	0.125281463
3.15	-10	-10	-10	-10	10	10	10	-10	10	-10	-10	-10	-0.0841698	0.0707599	0	0.103611641
3.15	10	-10	-10	-10	10	10	10	-10	-10	10	10	10	-0.0113908	0.0661725	0	0.08046318
3.15	-10	10	-10	-10	10	10	10	-10	-10	10	10	-10	-0.156579	0.136334	0	0.164899423
3.15	10	10	-10	-10	10	10	10	-10	10	-10	-10	10	-0.297502	0.0455247	0	0.304557879
3.15	-10	-10	10	-10	10	10	10	-10	-10	10	-10	10	-0.000158481	0.150074	0	0.15152771
3.15	10	-10	10	-10	10	10	10	-10	10	-10	10	-10	-0.0393485	0.0615804	0	0.066412736
3.15	-10	10	10	-10	10	10	10	-10	-10	-10	10	10	-0.252999	0.0126313	0	0.257314352
3.15	10	10	10	-10	10	10	10	-10	-10	10	-10	-10	-0.117149	0.188043	0	0.189204363
3.15	-10	-10	-10	10	10	10	10	-10	-10	10	-10	-10	-2.97E-05	0.37101	0	0.384413282
3.15	10	-10	-10	10	10	10	10	-10	10	-10	10	10	-1.05E-06	0.159074	0	0.161540297
3.15	-10	10	-10	10	10	10	10	-10	10	-10	10	-10	-0.0800415	0.210139	0	0.221230448
3.15	10	10	-10	10	10	10	10	-10	-10	10	-10	10	-0.00898386	0.287275	0	0.29204201
3.15	-10	-10	10	10	10	10	10	-10	10	-10	-10	10	-1.44E-06	0.242994	0	0.245944348
3.15	10	-10	10	10	10	10	10	-10	-10	10	10	-10	-0.000225752	0.404685	0	0.404719408
3.15	-10	10	10	10	10	10	10	-10	-10	10	10	10	-0.0023865	0.255076	0	0.258911236
3.15	10	10	10	10	10	10	10	-10	-10	-10	-10	-10	-0.0319291	0.291247	0	0.300406758
3.15	-10	-10	-10	-10	-10	-10	-10	10	10	10	10	10	-0.291247	0.0319291	0	0.300406758
3.15	10	-10	-10	-10	-10	-10	-10	10	10	-10	-10	-10	-0.255076	0.0023865	0	0.258911236
3.15	-10	10	-10	-10	-10	-10	-10	10	10	-10	-10	-10	-0.353172	0.0006071	0	0.353339498
3.15	10	10	-10	-10	-10	-10	-10	10	10	-10	10	10	-0.242994	1.44E-06	0	0.245944348
3.15	-10	-10	10	-10	-10	-10	-10	10	10	-10	10	-10	-0.287275	0.00898386	0	0.29204201
3.15	10	-10	10	-10	-10	-10	-10	10	10	-10	-10	10	-0.210139	0.0800415	0	0.221230448
3.15	-10	10	10	-10	-10	-10	-10	10	10	-10	10	-10	-0.159074	1.05E-06	0	0.161540297
3.15	10	10	10	-10	-10	-10	-10	10	10	-10	10	10	-0.356419	0.000391268	0	0.356955453
3.15	-10	-10	-10	10	-10	-10	-10	10	10	-10	-10	-10	-0.188043	0.117149	0	0.189204363
3.15	10	-10	-10	10	-10	-10	-10	10	10	-10	-10	-10	-0.0126313	0.252999	0	0.257314352
3.15	-10	10	10	-10	-10	-10	-10	10	10	-10	10	10	-0.0615804	0.0393485	0	0.066412736
3.15	10	10	-10	10	-10	-10	-10	10	10	-10	-10	-10	-0.150074	0.000158481	0	0.15152771
3.15	-10	-10	10	10	-10	-10	-10	10	10	-10	10	-10	-0.0455247	0.297502	0	0.304557879
3.15	10	-10	10	10	-10	-10	-10	10	10	-10	-10	10	-0.136334	0.156579	0	0.164899423
3.15	-10	10	10	10	-10	-10	-10	10	10	-10	-10	-10	-0.0661725	0.0113908	0	0.08046318
3.15	10	10	10	10	-10	-10	-10	10	10	-10	10	10	-0.0707599	0.0841698	0	0.103611641
3.15	-10	-10	-10	-10	10	10	-10	10	10	-10	-10	-10	-0.0719959	0.105725	0	0.125281463
3.15	10	-10	-10	-10	10	10	-10	10	10	-10	10	10	-0.473843	0.00237234	0	0.47629162
3.15	-10	10	-10	-10	10	10	-10	10	10	-10	-10	-10	-0.43948	0.000447864	0	0.439875209
3.15	10	10	-10	-10	10	10	-10	10	10	-10	10	10	-0.195994	0.0263293	0	0.198500327
3.15	-10	-10	10	-10	10	10	-10	10	10	-10	-10	-10	-0.393045	0.0024471	0	0.395514765

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	10	-10	10	-10	10	-10	-10	10	10	10	10	-10	-0.104757	0.150174	0	0.172654641
3.15	-10	10	10	-10	10	-10	-10	10	10	10	10	10	-0.172526	1.45E-06	0	0.176766186
3.15	10	10	10	-10	10	-10	-10	10	-10	-10	-10	-10	-0.355559	0.000569819	0	0.355689163
3.15	-10	-10	-10	10	10	-10	-10	10	-10	-10	-10	-10	-0.177213	0.0972565	0	0.177765315
3.15	10	-10	-10	10	10	-10	-10	10	10	10	10	10	-0.0182136	0.265356	0	0.273756222
3.15	-10	10	-10	10	10	-10	-10	10	10	10	10	-10	-0.00341751	0.10876	0	0.118915366
3.15	10	10	-10	10	10	-10	-10	10	-10	-10	-10	10	-0.258098	0.000420348	0	0.259247148
3.15	-10	-10	10	10	10	-10	-10	10	10	10	-10	10	-0.0278652	0.320458	0	0.324074292
3.15	10	-10	10	10	10	-10	-10	10	-10	-10	10	-10	-0.214611	0.140341	0	0.215320078
3.15	-10	10	10	10	10	-10	-10	10	10	10	10	10	-0.262017	0.000454069	0	0.263387627
3.15	10	-10	-10	-10	-10	10	-10	10	10	10	-10	-10	-0.00329556	0.173803	0	0.176293798
3.15	-10	10	-10	-10	-10	10	-10	10	10	10	-10	10	-0.126995	0.0978935	0	0.144682921
3.15	10	-10	-10	-10	-10	10	-10	10	-10	-10	10	-10	-0.406371	0.00235031	0	0.40983064
3.15	-10	10	-10	-10	-10	10	-10	10	10	10	10	10	-0.476906	0.000570908	0	0.477431013
3.15	10	10	-10	-10	-10	10	-10	10	10	10	-10	-10	-0.098208	0.0461797	0	0.123240185
3.15	-10	-10	10	-10	-10	10	-10	10	-10	-10	-10	-10	-0.325925	0.00373727	0	0.329169262
3.15	10	-10	10	-10	-10	10	-10	10	10	10	10	10	-0.159865	0.142343	0	0.178027217
3.15	-10	10	-10	-10	-10	10	-10	10	10	10	10	-10	-0.100844	0.0148907	0	0.107243266
3.15	10	10	10	-10	-10	10	-10	10	-10	-10	-10	-10	-0.392948	0.000692863	0	0.393154847
3.15	-10	-10	-10	10	-10	-10	-10	10	-10	-10	-10	10	-0.230604	0.103236	0	0.231013136
3.15	10	-10	-10	10	-10	-10	-10	10	10	10	10	10	-0.00151506	0.315336	0	0.321369309
3.15	-10	10	-10	10	-10	10	-10	10	10	10	10	10	-0.0038256	0.100869	0	0.115145324
3.15	10	10	-10	10	-10	10	-10	10	-10	-10	-10	-10	-0.186432	0.000302063	0	0.187760233
3.15	-10	-10	10	10	-10	10	-10	10	10	10	-10	-10	-0.0014403	0.363421	0	0.365805014
3.15	10	-10	10	10	-10	10	-10	10	-10	-10	10	10	-0.26819	0.145883	0	0.269179413
3.15	-10	10	10	10	-10	10	-10	10	-10	-10	10	10	-0.191373	0.00594756	0	0.196820597
3.15	10	10	10	10	-10	10	-10	10	10	10	-10	-10	-0.00317251	0.149074	0	0.153397148
3.15	-10	-10	-10	-10	10	10	-10	10	-10	10	10	-10	-0.223896	0.0651382	0	0.235164417
3.15	10	-10	-10	-10	10	10	-10	10	10	-10	-10	10	-0.309965	0.00241185	0	0.313163401
3.15	-10	10	-10	-10	10	10	-10	10	10	-10	-10	-10	-0.294095	0.000487375	0	0.294194393
3.15	10	10	-10	-10	10	10	-10	10	-10	10	10	10	-0.292771	1.56E-06	0	0.295586822
3.15	-10	-10	10	-10	10	10	-10	10	10	-10	10	10	-0.342469	0.00589015	0	0.346284632
3.15	10	-10	10	-10	10	10	-10	10	-10	10	-10	-10	-0.14284	0.113249	0	0.157638145
3.15	-10	10	10	-10	10	10	-10	10	-10	10	-10	10	-0.208835	1.17E-06	0	0.211080813
3.15	10	10	10	-10	10	10	-10	10	10	-10	10	-10	-0.297327	0.000271989	0	0.297748831
3.15	-10	-10	-10	10	10	10	-10	10	10	-10	10	-10	-0.131351	0.135738	0	0.145632936
3.15	10	-10	-10	10	10	10	-10	10	-10	10	-10	10	-0.0548773	0.228387	0	0.23441155
3.15	-10	10	-10	10	10	10	-10	10	-10	10	-10	-10	-0.00295313	0.0720664	0	0.080404247
3.15	10	10	-10	10	10	10	-10	10	10	-10	10	10	-0.19986	0.000267701	0	0.201145383
3.15	-10	-10	10	10	10	10	-10	10	-10	10	10	10	-0.0918543	0.272904	0	0.28196913

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	10	-10	10	10	10	10	-10	10	10	-10	-10	-10	-0.0853088	0.177826	0	0.177844374
3.15	-10	10	10	10	10	10	-10	10	10	-10	-10	10	-0.115946	0.00453974	0	0.122107655
3.15	10	10	10	10	10	10	-10	10	-10	10	10	-10	-0.0223629	0.116658	0	0.127813107
3.15	-10	-10	-10	-10	-10	-10	10	10	10	10	10	-10	-0.128816	0.112311	0	0.148795638
3.15	10	-10	-10	-10	-10	-10	10	10	-10	-10	-10	10	-0.417096	0.00266616	0	0.41963364
3.15	-10	10	-10	-10	-10	-10	10	10	-10	-10	-10	10	-0.389612	0.000741681	0	0.38974533
3.15	10	10	-10	-10	-10	-10	10	10	10	10	10	10	-0.206567	1.48E-06	0	0.21031881
3.15	-10	-10	10	-10	-10	-10	10	10	-10	-10	10	10	-0.449673	0.00224035	0	0.452650311
3.15	10	-10	10	-10	-10	-10	10	10	10	10	-10	-10	-0.0478293	0.160422	0	0.174534354
3.15	-10	10	10	-10	-10	-10	10	10	10	10	-10	10	-0.122635	0.00792977	0	0.126220977
3.15	10	10	10	-10	-10	-10	10	10	-10	-10	10	-10	-0.394912	0.000724273	0	0.395415539
3.15	-10	-10	-10	10	-10	-10	10	10	-10	-10	10	-10	-0.224592	0.106947	0	0.225198454
3.15	10	-10	-10	10	-10	-10	10	10	10	10	-10	10	-0.00119922	0.275503	0	0.279938602
3.15	-10	10	-10	10	-10	-10	10	10	10	10	-10	-10	-0.0031237	0.149859	0	0.15286519
3.15	10	10	-10	10	-10	-10	10	10	-10	-10	10	10	-0.295582	0.000445195	0	0.2966064
3.15	-10	-10	10	10	-10	-10	10	10	10	10	10	10	-0.0181378	0.319993	0	0.327125815
3.15	10	-10	10	10	-10	-10	10	10	-10	-10	-10	-10	-0.170548	0.144929	0	0.171068917
3.15	-10	10	10	10	-10	-10	10	10	-10	-10	-10	10	-0.2117	0.000430225	0	0.213131495
3.15	10	10	10	10	-10	-10	10	10	10	10	10	-10	-0.00350232	0.163402	0	0.170310834
3.15	-10	-10	-10	-10	10	-10	10	10	-10	10	-10	10	-0.234319	0.0253377	0	0.243161354
3.15	10	-10	-10	-10	10	-10	10	10	10	-10	10	-10	-0.311442	0.00208205	0	0.315361082
3.15	-10	10	-10	-10	-10	-10	10	10	10	-10	10	10	-0.403063	0.000381358	0	0.403545963
3.15	10	10	-10	-10	-10	-10	10	10	-10	10	-10	-10	-0.205701	1.06E-06	0	0.207632723
3.15	-10	-10	10	-10	-10	-10	10	10	10	-10	-10	10	-0.231021	0.00328315	0	0.234896309
3.15	10	-10	10	-10	10	-10	10	10	-10	10	10	10	-0.266217	0.0697652	0	0.277073955
3.15	-10	10	10	-10	-10	-10	10	10	-10	10	-10	-10	-0.210401	0.0524218	0	0.212852433
3.15	10	10	10	-10	-10	-10	10	10	10	-10	-10	10	-0.319122	0.000424602	0	0.319291148
3.15	-10	-10	-10	10	-10	-10	10	10	10	-10	-10	10	-0.141714	0.107628	0	0.142310261
3.15	10	-10	-10	10	-10	-10	10	10	-10	10	10	-10	-0.0475722	0.242862	0	0.251385065
3.15	-10	10	-10	10	-10	-10	10	10	-10	10	10	10	-0.111496	0.0302018	0	0.116130835
3.15	10	10	-10	10	-10	-10	10	10	10	-10	-10	-10	-0.11282	0.000133642	0	0.115148166
3.15	-10	-10	10	10	-10	-10	10	10	-10	10	-10	-10	-0.0113698	0.290965	0	0.294376661
3.15	10	-10	10	10	-10	-10	10	10	10	-10	10	10	-0.179153	0.151428	0	0.180497505
3.15	-10	10	10	10	-10	-10	10	10	10	-10	10	-10	-0.118216	0.00834483	0	0.119977222
3.15	10	10	10	10	-10	-10	10	10	-10	10	-10	10	-0.0300784	0.0773947	0	0.088023747
3.15	-10	-10	-10	-10	-10	-10	10	10	-10	10	-10	-10	-0.166898	0.0753863	0	0.180024481
3.15	10	-10	-10	-10	-10	-10	10	10	10	-10	10	10	-0.386489	0.0022051	0	0.387572997
3.15	-10	10	-10	-10	-10	-10	10	10	10	-10	10	-10	-0.331377	0.000280617	0	0.33178879
3.15	10	10	-10	-10	-10	-10	10	10	-10	10	-10	10	-0.242875	1.21E-06	0	0.244951932
3.15	-10	-10	10	-10	-10	-10	10	10	10	-10	-10	10	-0.2858	0.00707844	0	0.289790244

TransZ	LC1	LC2	LC3	LC4	LC5	LC6	LTC1	LTC2	LTC3	LTC4	LTC5	LTC6	ZMin	ZMax	LMin	LMax
3.15	10	-10	10	-10	-10	10	10	10	-10	10	10	-10	-0.199717	0.119836	0	0.213806049
3.15	-10	10	10	-10	-10	10	10	10	-10	10	10	10	-0.250714	1.56E-06	0	0.25383186
3.15	10	10	10	-10	-10	10	10	10	10	-10	-10	-10	-0.247452	0.000402572	0	0.247551596
3.15	-10	-10	-10	10	-10	10	10	10	10	-10	-10	-10	-0.0898673	0.141525	0	0.141662587
3.15	10	-10	-10	10	-10	10	10	10	-10	10	10	10	-0.0982176	0.234927	0	0.246014624
3.15	-10	10	-10	10	-10	10	10	10	-10	10	10	-10	-0.0398142	0.0786004	0	0.095196992
3.15	10	10	-10	10	-10	10	10	10	10	-10	-10	10	-0.149974	0.000243856	0	0.151473563
3.15	-10	-10	10	10	-10	10	10	10	-10	10	-10	10	-0.0528612	0.283026	0	0.288038298
3.15	10	-10	10	10	-10	10	10	10	10	-10	10	-10	-0.126381	0.186459	0	0.188416597
3.15	-10	10	10	10	-10	10	10	10	10	-10	10	10	-0.155697	0.0143265	0	0.161808967
3.15	10	10	10	10	-10	10	10	10	-10	10	-10	-10	-0.00303793	0.126708	0	0.131442897
3.15	-10	-10	-10	-10	10	10	10	10	10	10	10	10	-0.184045	0.0876438	0	0.198367002
3.15	10	-10	-10	-10	10	10	10	10	-10	-10	-10	-10	-0.350082	0.00254643	0	0.352714014
3.15	-10	10	-10	-10	10	10	10	10	-10	-10	-10	-10	-0.439372	0.000767031	0	0.439576015
3.15	10	10	-10	-10	10	10	10	10	10	10	10	10	-0.147474	0.0150344	0	0.151865422
3.15	-10	-10	10	-10	10	10	10	10	-10	-10	-10	-10	-0.38232	0.00315139	0	0.385747689
3.15	10	-10	10	-10	10	10	10	10	10	10	-10	10	-0.102937	0.135755	0	0.15451501
3.15	-10	10	10	-10	10	10	10	10	10	-10	-10	-10	-0.0663968	0.0504455	0	0.096334769
3.15	10	10	10	-10	10	10	10	10	-10	-10	10	10	-0.443183	0.000558703	0	0.443723846
3.15	-10	-10	-10	10	10	10	10	10	-10	-10	10	10	-0.277998	0.0994959	0	0.278797629
3.15	10	-10	-10	10	10	10	10	10	10	10	-10	-10	-0.00131894	0.308814	0	0.311542655
3.15	-10	10	-10	10	10	10	10	10	10	10	-10	10	-0.00309835	0.0947128	0	0.10142488
3.15	10	10	-10	10	10	10	10	10	-10	-10	10	-10	-0.236314	0.000325916	0	0.237452207
3.15	-10	-10	10	10	10	10	10	10	10	10	10	-10	-0.00174476	0.353264	0	0.358326723
3.15	10	-10	10	10	10	10	10	10	-10	-10	-10	10	-0.221287	0.136092	0	0.221882604
3.15	-10	10	10	10	10	10	10	10	-10	-10	-10	-10	-0.152405	0.000310947	0	0.154486285
3.15	10	10	10	10	10	10	10	10	10	10	10	10	-0.00347697	0.138913	0	0.149148707

G: R Positioning Output of Case Study Results

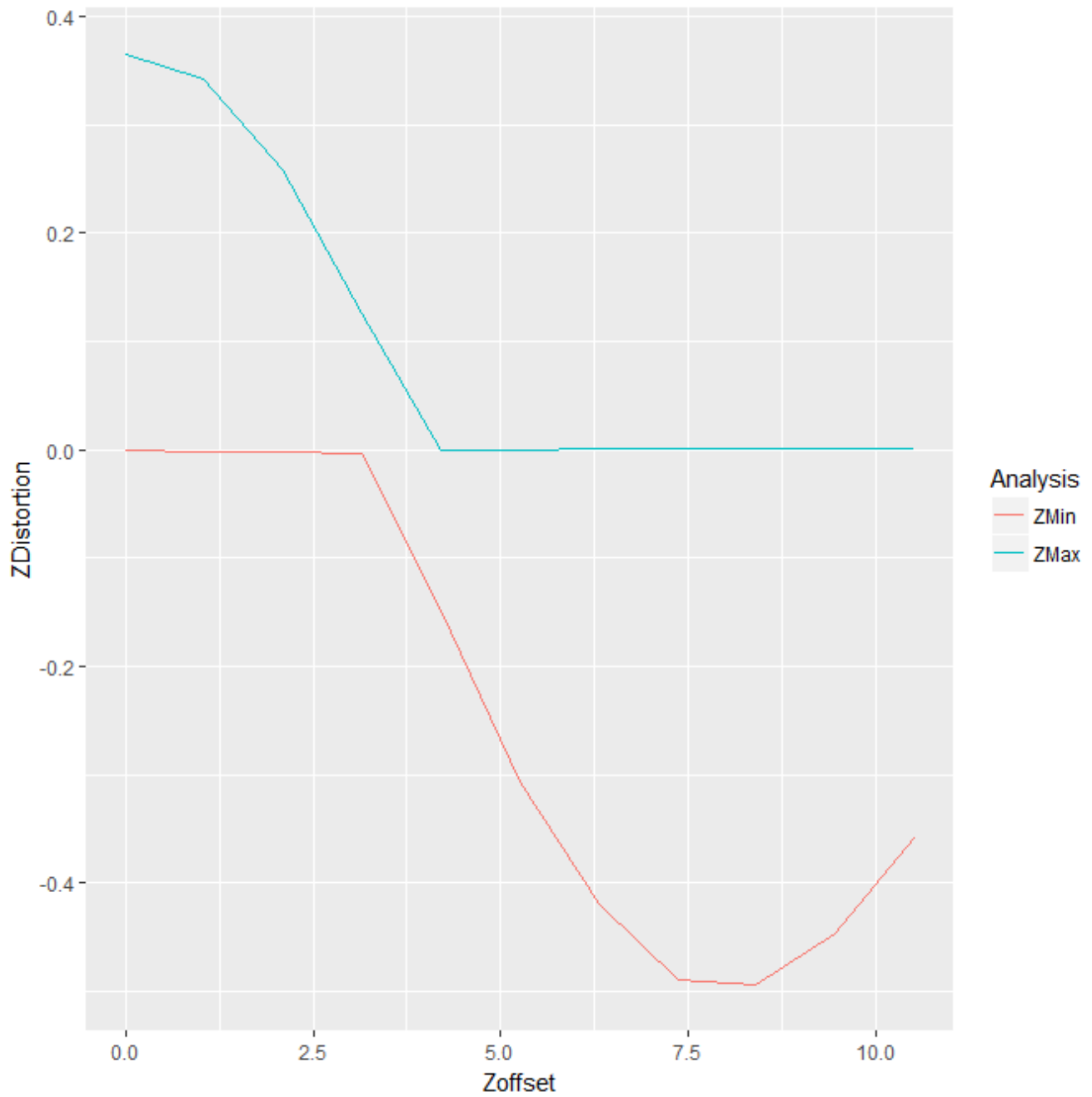


Figure 134: R report for position analysis of the case study, in x axis is the variation in z offset going from 0 mm to 10.5 mm every 1.05 mm, in y axis the distortion in z direction (mm).

H: R Output of the 12 Coefficients Variation, 2 levels, 1/16 Fractional Factorial Design for the Case Study

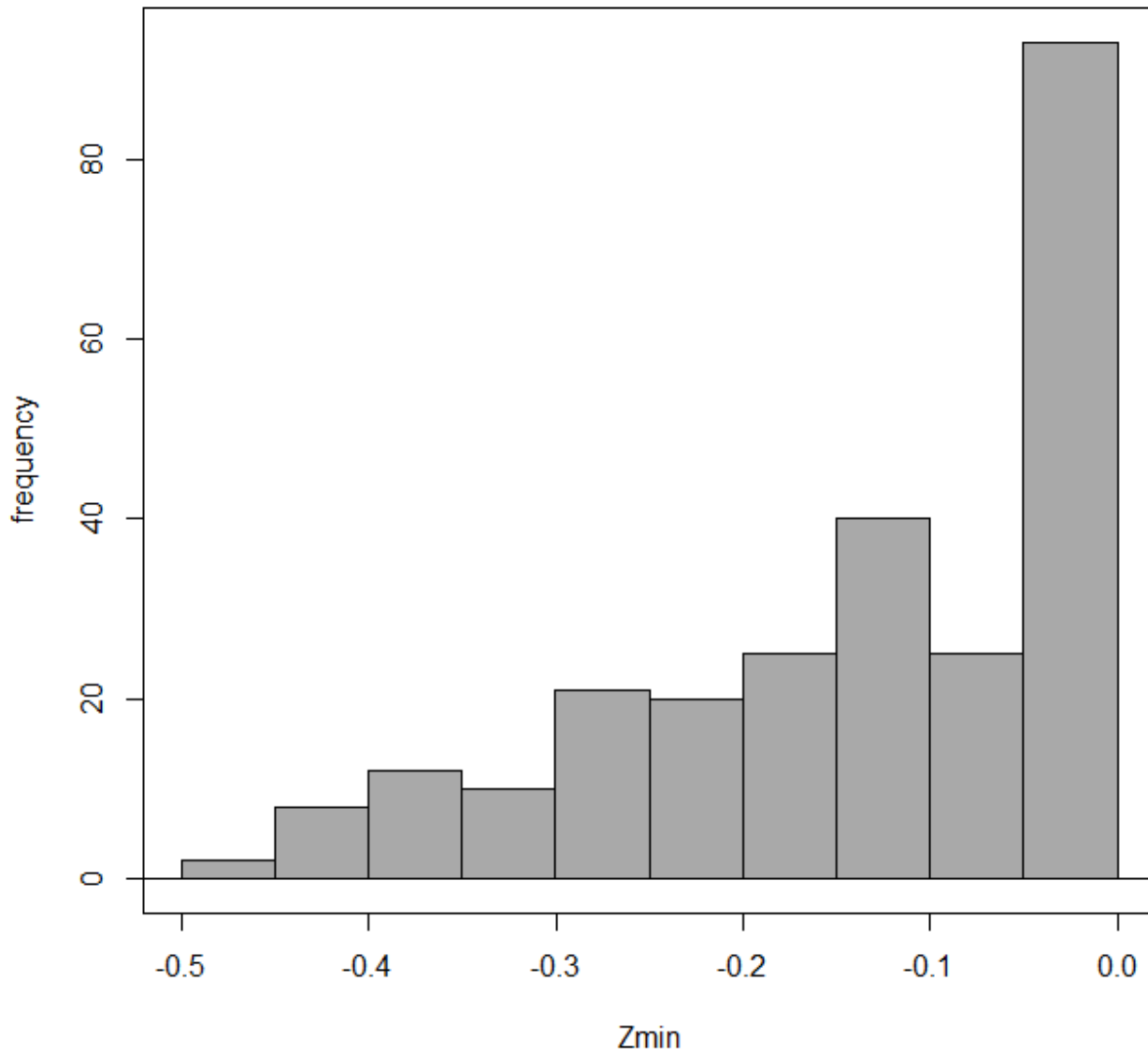


Figure 135: Histogram of the results for the 1/16 fractional factorial design of the case study.

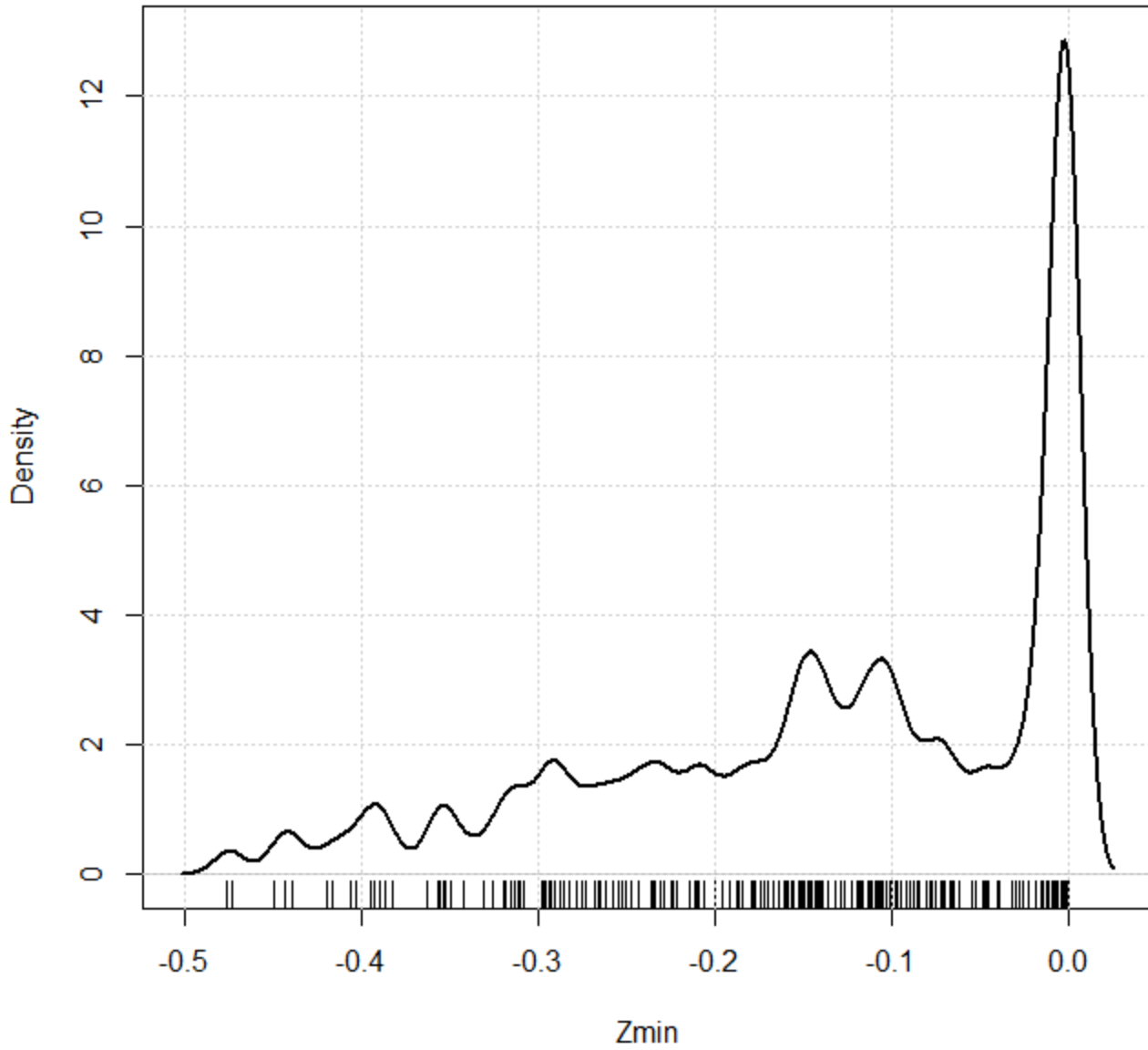


Figure 136: Density plot of the results for the 1/16 fractional factorial design of the case study.

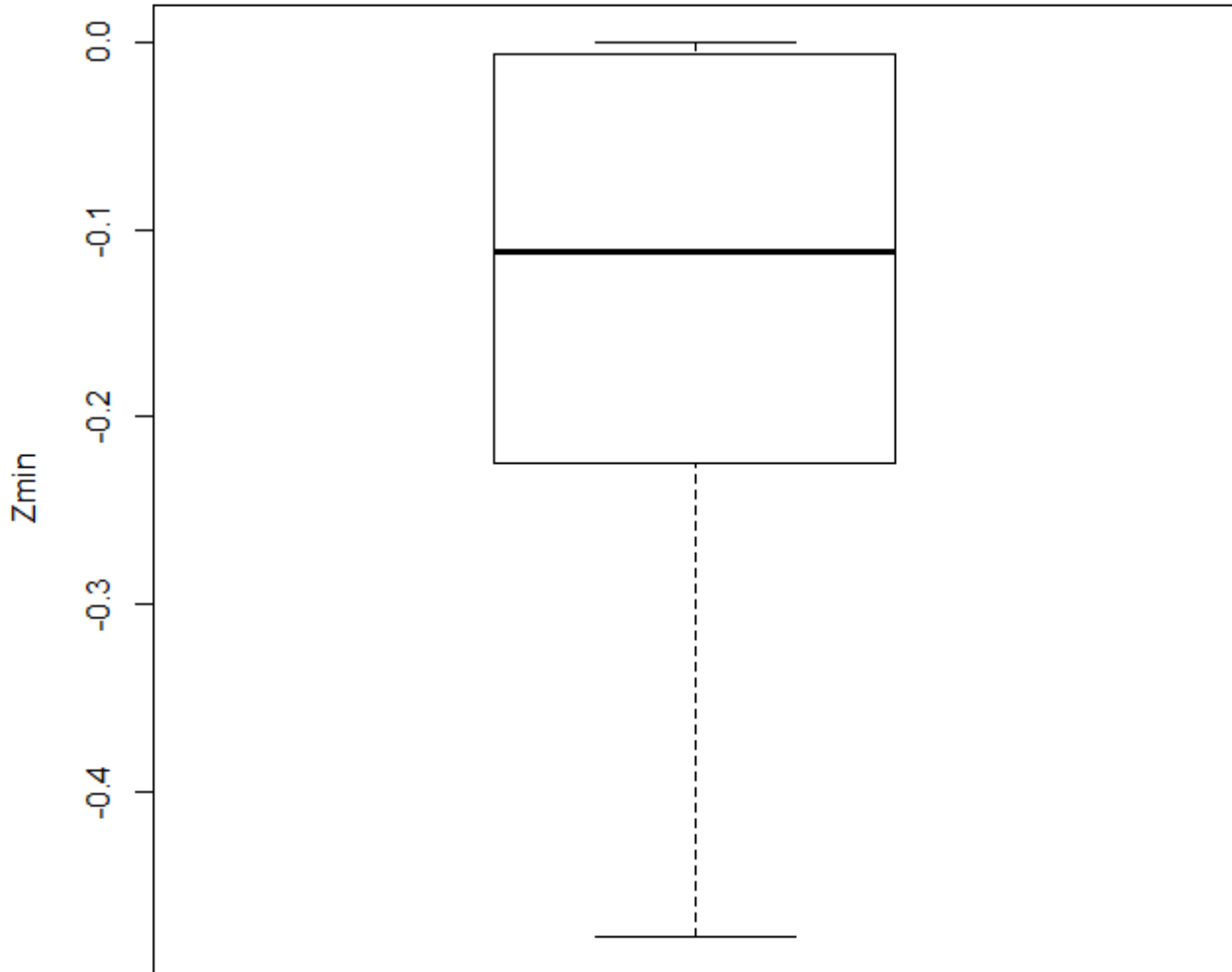


Figure 137: Box plot of the results for the 1/16 fractional factorial design of the case study.

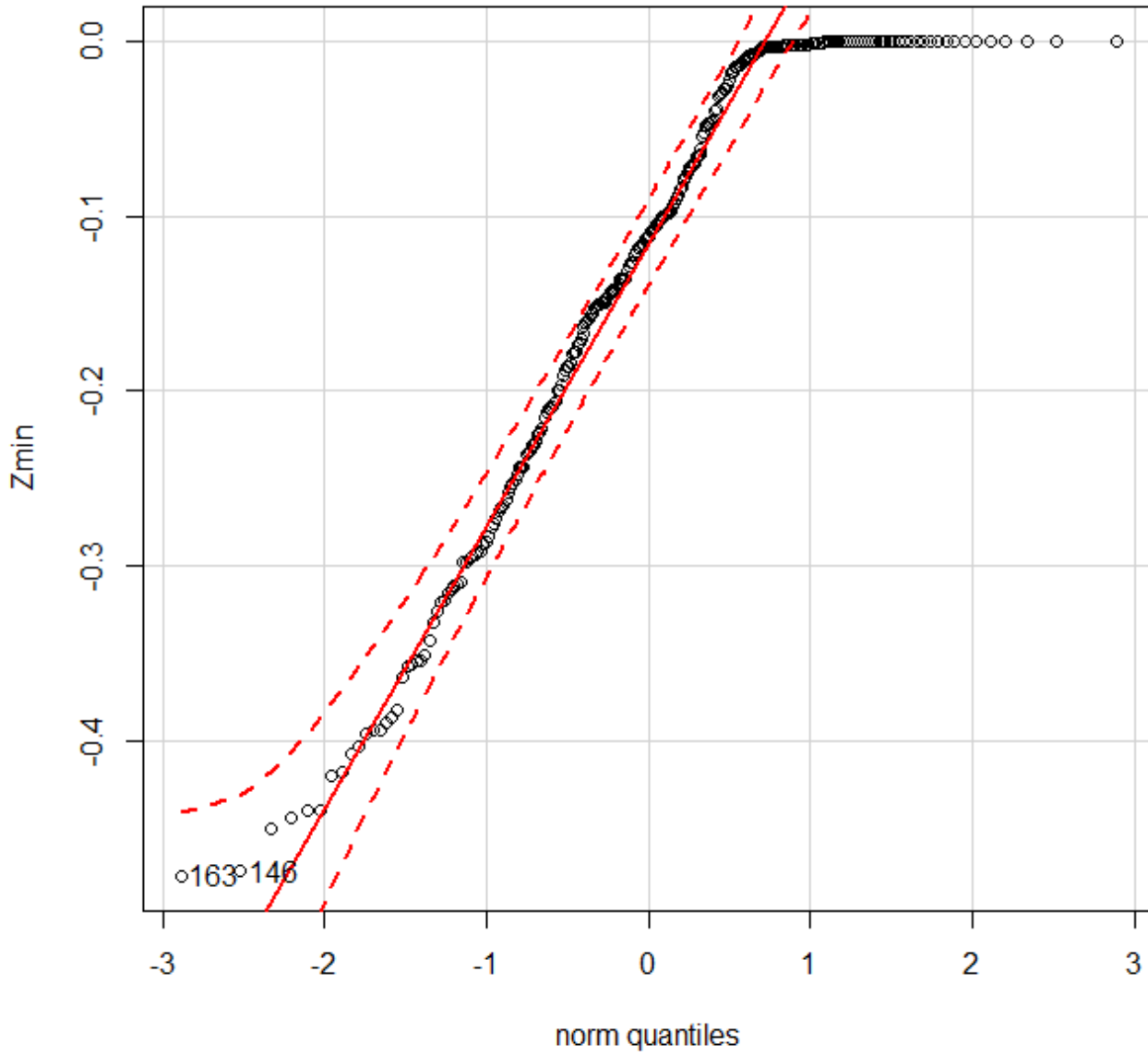


Figure 138: Quantile comparison plot of the results for the 1/16 fractional factorial design of the case study.

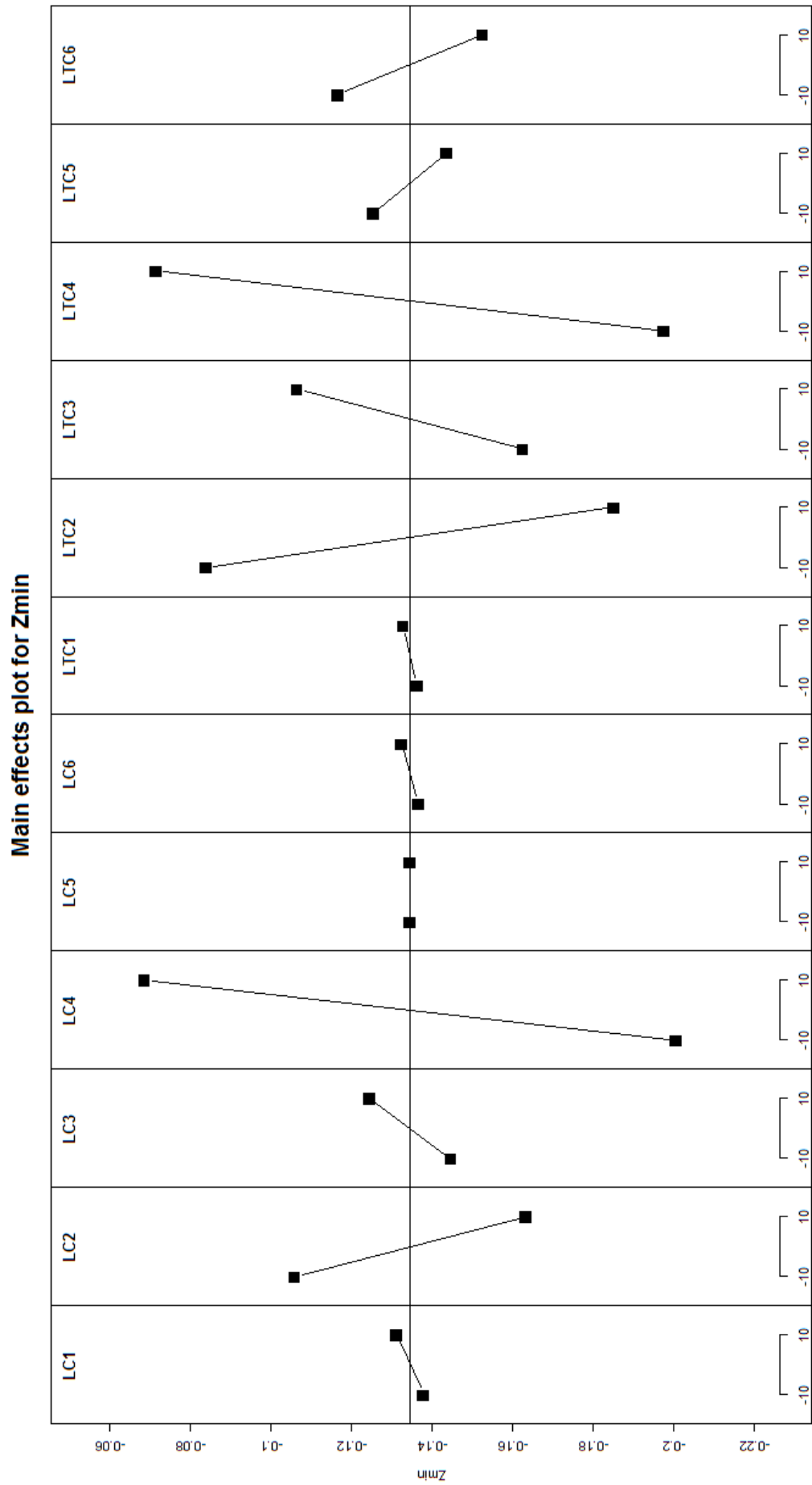


Figure 139: Main effect plot of the results for the 1/16 fractional factorial design of the case study.

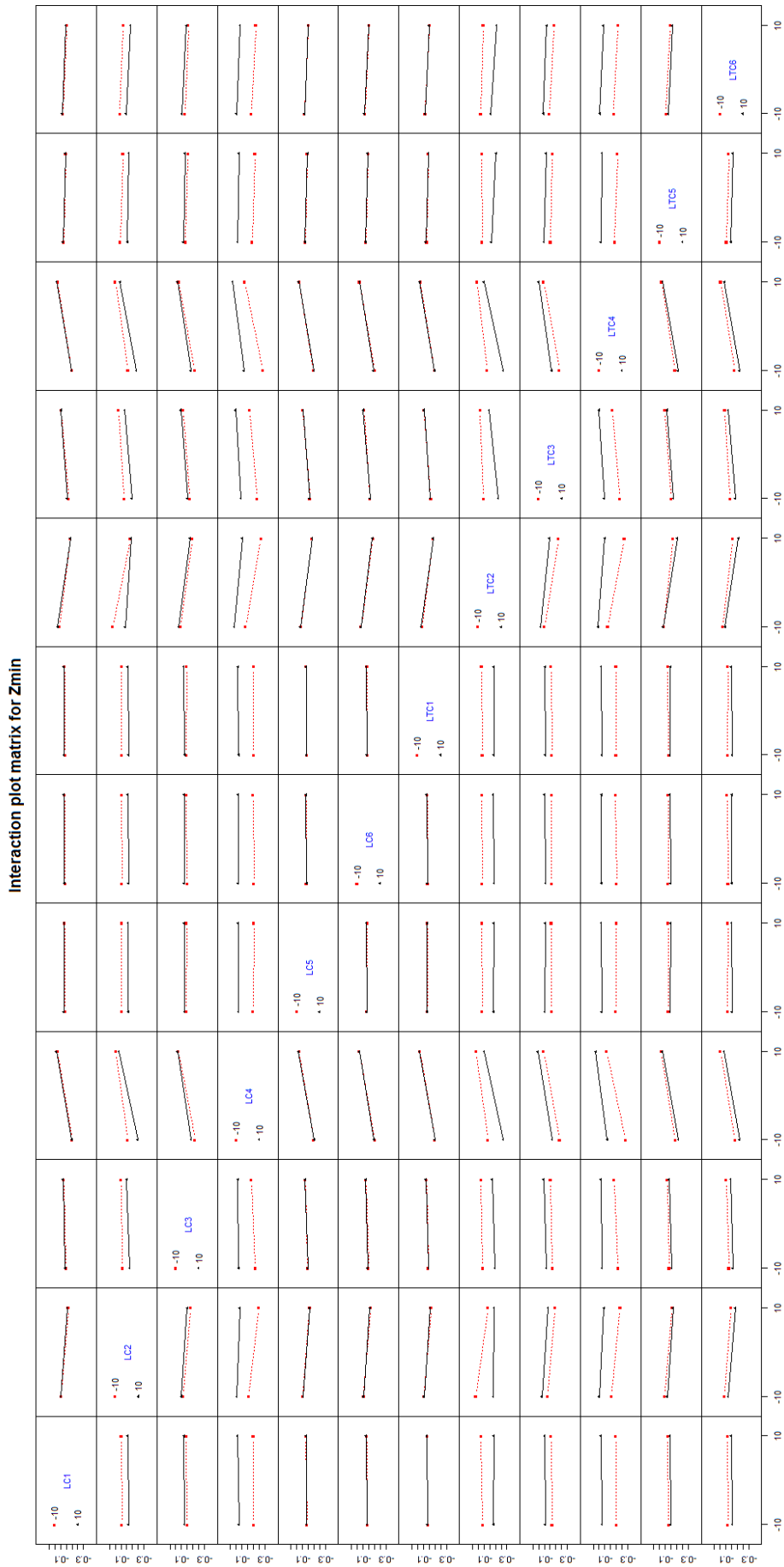


Figure 140: Interaction effect plot of the results for the 1/16 fractional factorial design of the case study.