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Efficiency of Lightweight Structural Forms: The Case of Tree-like Structures - A comparative Structural Analysis

A master's thesis submitted for the degree of
"Master of Science"

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ABSTRACT

This work addresses the structural efficiency of lightweight tree-like structures for three case studies: Stuttgart Airport, Beaverton Library, and Thermal Bad Oeyenhausen.

The case studies are simulated using *Build* simulation software, to determine the stresses induced in each structure. The material efficiency and shapes are explored in terms of load bearing structures.

Hybrids of the above structures are formed to compare the pattern morphology used by various types of tree-like structure and assess the structural behavior. In addition, (steel, wood and concrete) materials are compared to determine which would have better structural performance.

In order to show the resemblance between the growing trees and the tree-like structures, an example of both cases is simulated and stresses evaluated.

Results show that, in general, the minimum stress and deformations are obtained for steel. Structures made out of this material also exhibit higher load bearing capability, optimum stability factors and the best geometric efficiency, in spite of higher specific weight (10 times wood, and 3 times concrete).

1 Introduction to Lightweight Structures

There are various means to create design in architecture. One may create a shell and decorate it to achieve the desired effect, or create a structural system where the structure is vital to the final design of the building. The second approach is the subject of this work.

The idea of building anything out of lightweight materials started in traditional cultures throughout the world, where the value of straw, grasses, and reeds as building materials, have been used efficiently in combination with earth and timber to create shelter for thousands of years. In Asia, Latin America and Africa, some houses, bridges, and buildings were built using often bamboo materials. In many places, steel, concrete, and glass have replaced bamboo as a building material or given it the reputation of being the "poor man's wood" (Simon Velez, 2000, p8). Nomadic cultures, long before establishing the first human settlement, were aware of the benefit from lightweight housing. They were easily constructible/mountable and, most importantly transportable. However these methods are considered primitive today. During the evolution of building, such materials were replaced with heavyweight constructions e.g. pyramid of Egypt, castles, palaces, temples etc.

During the Gothic period, an attempt to reduce the mass of materials was made due to larger indoor illumination requirements. Lightweight structures in Gothic architecture may sound controversial; since stone is the primary material and its specific weight is high compared to other masonry materials. However, by introducing efficiently the appropriate geometry, builders reduced the use of stone, providing even greater structural stability and reliability. In removing a significant amount of stone, it was possible to enlarge the windows and increase the indoor luminance (Mark, Robert, 1994, p 105).

Dematerialization and lightweight construction had been under discussion for a long time to rationalize the use of materials. Increased use of steel and glass in building, are indicators of modernization and of construction that is calculated in terms of static buildings and planned economically (Winfried Nerdinger, 2005, p 11).

The German architect and scientist Frei Otto spent his entire life studying the form-finding processes of nature. As an architect, he used these processes to develop and build many structures (Winfried Nerdinger, 2005, p 11). He eventually carried out experimentation in form finding using lightweight structural materials. He worked on tents and soap films, pneus and hydros, suspended constructions, grid shells, and branching structures. Frei Otto worked on the principles to reduce the mass of the material and at the same time provide structural efficiency (Winfried Nerdinger, 2005, p39)[1].

"Objects which carry loads while possessing relatively little mass are termed 'light'. Technically speaking they are 'lightweight constructions'" (Frei Otto, 1979, IL 23. Kraftweg. Tra un Bic, p 54).

In building design, a lightweight structure requires less material and therefore provides maximum and rational use of materials. Introducing optimal load bearing geometry provides sufficient strength and consequently reduces the waste of resources.

The first theories of lightweight construction appeared during the 19th century. The British physicist James Clark Maxwell (1831 – 1879) and A.G. Michel, who became famous for his structural optimizations, may be regarded as founders of the discipline (Winfried Nerdinger 2005, p 49). Vladimir Shukhov (1863-1939), Richard Buckminster Fuller (1895-1983), Konrad Wachsmann (1901-1980) and Max Mengeringhausen (1903-1999), who collaborated with Frei Otto on projects such as the 1967 Montreal pavilion, used the slogan "Lightweight construction – a requirement of our time" as early as 1940 in the title of a publication on building and bridge construction (Fritz Leonhardt, 1940 pp 128 132). Nevertheless, this requirement seems too optimistic to replace the existing heavyweight structures that occur in building design every day.

Lightweight structures are a complex matter and require a greater intellectual effort rather than a physical one. The basic rules of lightweight structures are (Windfried Nerdinger, 2004, p 40):
- Avoid bending stresses.
- Carry compression forces over short distances to avoid stability problems and unnecessary added mass in the struts.
- When compression forces must be carried across long distances, incorporate them into self-stabilizing systems (prestress, e.g., spoke wheels,).

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[1] *Frei Otto Complete Works Lightweight construction Natural Design. "The forms of relatively light weight construction are rarely coincidental. Usually, they are the result for development and optimisation processes which, for whatever reason, follow the principle of the reduction of mass. We call this principle the lightweight construction principle". .*

- Give planar components in compression appropriate shape to secure them against stability failure.
- "Short-circuiting" the forces within the load-bearing system can result in lightweight structures, and thereby allow simple foundations.

1.1 Tree-Like Structures - State of Research on Lightweight Structures

Light structures are defined as tensile/tension structures, frame supported, air supported, air inflated, cable net, cable-and-strut (also referred to as tensegrity), geodesic domes, and grid shells. The majority of published materials cover the above mentioned systems, whereas only a few books and articles are available to cover tree-like structural behaviour in architectural design.

Trees and forests have inspired structural forms in architecture. The German Architect, Frei Otto, carried out systematic research on lightweight and adaptable construction and described buildings as "Natural Construction" (Windfried Nerdinger, 2005, p40). He published papers on fundamental aspects of the relationship between architecture and nature. His remarkable works include: suspended construction, dome shells, grid shells, inverting the suspended shades etc. Frei Otto worked on tree-like columns and on the model of branching structures (Winfried Nerdinger 2005, p 27).

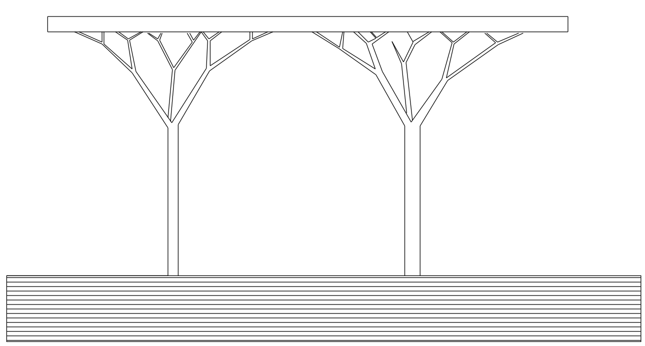


Fig 1.1.1 Design sketches by Frei Otto (Schultz *et al*, 2000, p 191)

Branching structures exhibit a particularly close relationship between the course of the forces and their shape, both in their overall appearance and in the nature of the structure itself. It is a functional combination between the roof construction and supporting structures. The advantage of the tree-like branching system is to have short distances from the loading points to the supports.

Frei Otto developed many different branching structures. He used hanging models to mould designs for structural support of footbridges, for conference halls and for large hexagonal grid domes. Eventually, Frei Otto developed systems of branched columns which he managed to convert into a harmonious structure of the dome that became melded into a single structure (Windfried Nerdinger, 2005, p 28).

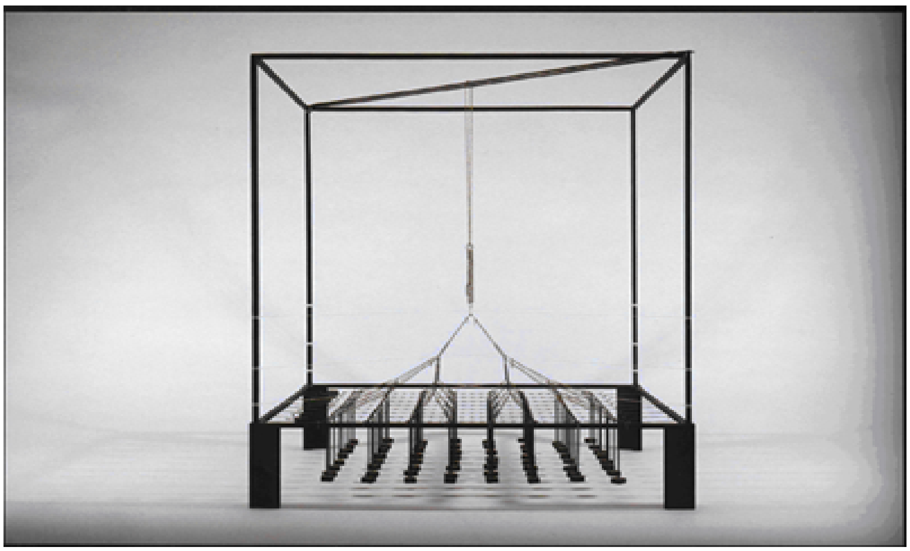


Fig 1.1.2 Frei Otto's hanging models of branching systems (Windfried Nerdinger, 2005, p 67)

Branching structures are usually referred to as tree-like structures/columns. However, their action cannot be compared with that of a natural tree. While the branches of a tree are under bending stress, bending forces are systematically avoided in technically constructed tree-like structures (Windfried Nerdinger, 2005, p 27). The inner structure of the tree-like columns represents a type of framework that is unique in the construction industry. It is not a truss with a triangular structure, which would brace the structure, allows articulation joints between the truss elements, and prevents bending even under alternating loads. In the tree-like column, therefore, the individual elements must be rigidly connected at the joints. A tree-like column is particularly well suited for only the one main load scheme for which it is optimized. All other loading conditions will cause bending stresses within the structure.

The architectural articulation of tree column occurs in a great number of buildings, masterpieces that have lightweight structures, e.g., *Orient Station* in Lisbon, Portugal, by

Santiago Calatrava (Andrew W. Charlson, 2005, p192), Steel tree-columns are also the main structural element in the interior of *Stuttgart Airport Terminal* (Andrew W. Charlson, 2005, p192). Structural branches penetrate the wall glazing at first floor level to support the entrance canopy. Tree-like columns were introduced in the renovation and modernization of Olympic Stadium, Berlin, to support the roof membrane (Volkwin Marg, 2006). The tree-like columns are branched in four support elements.

Over the past 30 years, there was a great improvement in designing lightweight canopy structures for sports' arenas. Consequently the design approach of removing heavy structures provides lighter and mobile structures.

Tree-like structures (columns) find a very effective application in bridge design and other large span structures. It makes them useful for public buildings such as airports, sport arenas, railway stations, shopping malls, etc.

The tree columns or structures terminology is used among the Architecture and Engineering community only due to the appearance of the structures. However, the structural systems using tree columns have completely different load bearing behaviour as opposed to natural growing trees. This will become evident later in the comparative structural simulation analysis part (see chapter 4).

1.2 Factors Influencing Tree Growth and Form and its Applications in Architecture

Trees are an intriguing paradigm of growth and development. They represent much more than an aggregate of twigs and branches attached to a common axis. Trees growth does not evolve equally in all directions. One of the main effects on the trees' form is gravity, because it is a continuous, uniform applied force. The branches do not grow randomly in all directions but are regulated by the effects of gravity and light. The shape of the tree crown is then dependent on the internal branching patterns that permit optimal use of space and light. Light, gravity, and the struggle for growing space interact to determine the overall size and shape of trees. In architecture, light and space are pre-determined; the shape and dimension of the tree-like support is only defined according to the load it is expected to bear. Once defined during the planning stage, unlike trees in nature, the tree-like structure cannot grow any further.

Tree models are based on branching structures of internodes (branches) and nodes (bifurcations). The branch is defined physically by its length (*l*), diameter (*d*), start point (*s*) and direction (*l*). The bifurcation is characterized by the angles j_i (i=1, 2) between the axes of the parent branch and the child branches and by the ratios in length, l_i/l_0, and diameter, d_i/d_0 between the parent branch and the child branches. By the time one of the child branches bifurcates again, it will normally not be part of the same plan, but have different orientation, defined by a divergence or twisting angle, q_i. The orientation of a branch is a function of the parent branch's orientation, j_i, the bifurcation angle and the divergence angle, q_i.

A branching system exhibits a repetitive hierarchical organization, where its parts are geometrically similar to the whole. This self-similarity property is a distinctive feature of fractals.

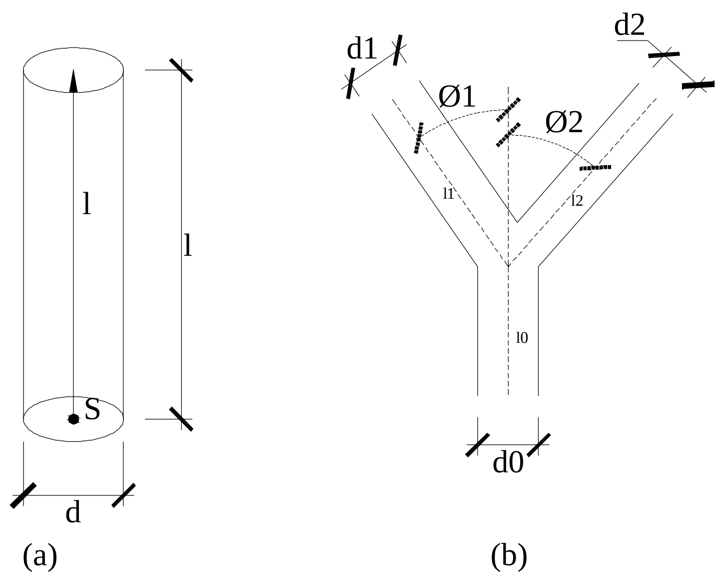


Figure 1.3 Branching structure consist of internodes, (a) and nodes (b)

During their lifetime, trees are constantly subjected to stresses such as compression and tension due to differential rates of growth of the branching system, increases in total mass, and the effects of bending and swaying under the influence of wind. The differential warming and cooling of various parts of the tree also induces thermal stresses, such as expansion and shrinking of its tissues.

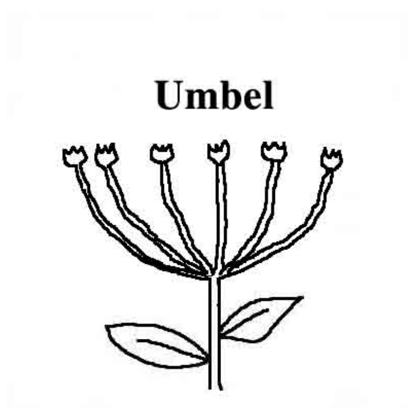
For structural simulation purposes, the effects of thermal stresses on tree-like structures will be neglected. The structural bending under the influence of winds is also negligible[2]; only stresses induced by the dead load and by hypothetical earthquakes will be simulated. The tree-like structures are simulated as static elements, as opposed to real trees, seen as dynamical elements of nature (Linsen, L, 2005; Hart, J.C. 2003; Prusinkiewicz, P. 1998).

1.3 The Umbel System

Tree-like load bearing structural systems applied in architecture are frequently termed tree-like columns in the literature. However, such structures more closely resemble umbel systems, where the total load is distributed to one point and from there transmit the total load via a single member to a support point, the point of application of the reaction force providing total equilibrium (Schultz *et al*., 2000, p190).

The word *umbel* comes from, *umbella* in New Latin, and from Latin, umbrella (meaning sunshade, parasol, derivation of *umbra* shadow, shade), a racemose inflorescence typical of the carrot family in which the pedicels arise from about the same point to form a flat or rounded flower cluster.

The umbel system can be visualized as a special case of the tree-like system, where a number of short branch stalks (called pedicles), which are equal in length, spread from a common point, somewhat like umbrella ribs.



[2] Structural Engineers have accounted for climatic effects (wind, snow, etc), thus, deformations due to climatic effects are controlled.

Fig 1.1.4 Umbel system, all the branches of the inflorescence radiating from a single point[3].

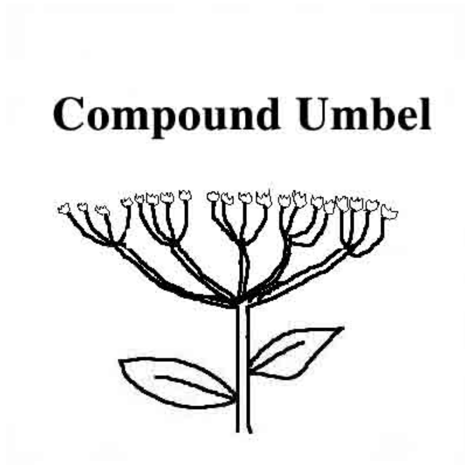


Fig 1.1.5 Compound umbel system, each branch of the umbel terminating in a smaller umbel[4].

The analogy of the tree-like structures with the umbel system is schematically illustrated in the following figure.

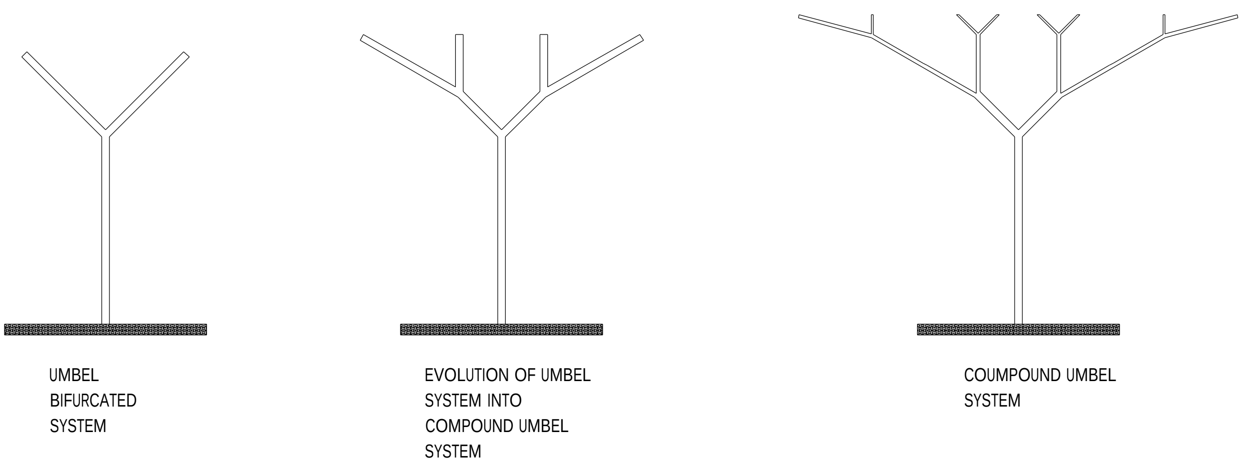


Fig 1.1.6 Structural umbel systems from umbel bifurcated system to compound umbel systems.

All members must be loaded exclusively in compression. As mentioned above, this is only possible when the lines of action of all forces intersect at one point. However, this is not typical of the majority of umbel columns, e.g. for supporting long-span roofs of heavy floors.

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[3] http://courses.bio.psu.edu/bio414/terms.html (2006-09-17)

This makes it necessary to introduce additional tension and or compression members. The example of umbel columns supporting a roof structure reveals that considerable tensile and compression forces have to be accommodated at roof level in order to achieve overall equilibrium.

The morphology, or rather the arrangement of members, for umbel columns is determined by using models, assisted by computer or hand drawn graphics. With two-dimensional load-bearing systems, determining the geometry using graphical methods leads to a detailed understanding of the relationships between the arrangement of members and forces.

It should be pointed out that the structure is composed of members loaded exclusively in compression for one loading case, i.e. the one determining the form. For all other loading cases, the bending strengths of the members, and especially the nodes, must be used.

The members of steel umbel columns are best made from steel tubes, the nodes of cast steel. Cast steel nodes are the easiest way of achieving the often complex geometry of such junctions. Cast nodes allow the flow of forces to be organized very effectively. The members are welded to the nodes from cast steel (Schultz *et al.*, 2000).

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[4] http://courses.bio.psu.edu/bio414/terms.html (2006-09-17)

2 Analysis of Tree-like Structural Behaviour using BUILD Simulation Software

The present worked will be developed using BUILD software. The program BUILD allows prompt assessment of structural behaviour for particular construction types through detailed analysis of the stress distribution. This is carried out based on predefined loads and taking into consideration the elastic stability.

Structures can be further sensibly analyzed based on deformations resulting from applied ranges of loads (from dead loads to earthquake scale). Graphical illustrated analysis (e.g., in stress or in stability analysis) are used to assess the weak points of a particular structure.

2.1 Software Description

The program approximates the real construction by using finite difference method, that is, by applying a grid to the model (using linear changeable sections) and applying plane elements computed by linear theory of first (and second) order to analyze its own values to simulate the stress and to examine stability.

In practice, the program uses finite different method to replace the continuous problem domain with the finite difference mesh containing a finite number of grid points. In this way, to represent a dependent variable *s* on a two dimensional spanned by Cartesian coordinates *(x, y)*, the continuous function *s (x, y)* is replaced by *s* (*i* D *x*, *j* D *y*).

The BUILD Program is part of the professional programs to analyze building structures; however it lacks interactive graphical input, AUTOCAD for teaching purposes.

2.2 Definition of BUILD variables

BUILD is not graphically interactive, thus, to quantify a problem, for instance the load and the state of one particular construction, the input data is introduced to describe problems alphanumerically The easiest way to input data is by using the Teddy text editor from SOFISTIK Company. “Teddy” program at the same time makes possible the immediate activation of BUILD within Windows operating system, performing graphical display and giving numerical results.

2.2.1 **Input Variables**

(a) Geometrical definition of the structure to be analyzed. The dead load is quantified based on the definition of the dimensions of cross sections and type of materials employed in the structure.

(b) Standard Values of construction material properties were used from the BUILD database (Dobivisek, B. 2005):

- **Young's modulus (E)**

  The ratio of stress to strain for a certain material experiencing either tensile or compressive stress defines the modulus of elasticity. The Young's modulus applies to tensile stress when the sides of the beam are not constrained. It is an elastic constant that describes linear elastic behavior.

- **Poisson's ratio**

  Considering that the material is subjected to uniaxial stress, the Poisson's ratio represents the ratio of the transverse strain, divided by the axial strain. Most engineering materials have a Poisson's ratio between 0.0 and 0.5.

- **Maximum admissible stress (fc)**: as defined in EUROCODE, is the maximum admissible compressive stress that a construction material can withstand. In BUILD, fc is defined as the maximum admissible stress (compression, tension, or both). The admissible values for tension, compression and shear stresses can be input in the material database of BUILD.

- **Earthquake's Natural Frequencies:** set of frequencies starting from the lowest natural frequency that originate corresponding mode shapes. Dynamical analyses are computed for the natural modes and frequencies of free oscillations of the structure. The computing of the natural frequency starts with the number 1 which is the lowest natural frequency..

- **Specific weight** The specific weight (also known as the unit weight) is the weight per unit volume of a material. The materials are predefined in the program and are used without the input using the following values (kN, m^3):

  i. **Concrete 20.5**

ii. **Steel** **78.5**

iii. **Wood** **8.0**

2.2.2 Output Variables

The program BUILD examines structural deformations, stability and the natural oscillation frequency under full load (Dobivisek, B., 2005, p 17).

(a) **Stress -** When a load (external force) acts on a structural element, it is resisted by an internal force, or stress (•).

(b) **Relative Stress, s/*fc*:** The relative stress is a measure of the deformation for a specific material. In the BUILD program, sigma/fc refers to the ratio between the existing stress in the structure and the admissible stress of the material. A deformation with s• *fc* becomes irreversible.

(c) **Deformation** – can be defined as strain or deflection (displacement). Strain is the change of volume/ and/or shape of a material, or part of it, as a response to the stresses in the material. Deflection is described as the degree to which a structural element is displaced under the influence of a load. BUILD defines u (m) as displacement of the structural elements under a load.

(d) **Bifurcation factor (also known as safety or stability factor)** Stability may be perturbated by the breaking or collapse of the structure. Therefore, it is important to quantify the maximum load (bifurcation load) beyond which the system is considered unstable. Once the stability factor value is exceeded, the structure becomes increasingly unstable, even without further increases in the applied external load. The bifurcation or stability factor indicates how many times the dead load of the structure can be exceeded without the latter becoming unstable.

(e) **Maximum load bearing capability** - The load that induces the maximum allowable stress in the structure. In build this is defined as maximum sigma beam.

(f) **Load Cases –** Several load cases are tested using BUILDto answer the research question *how does the same tree-like structural typology behave under different loads and using different materials?*

iv. Loadcase 1 (LC1) – corresponds to the dead load of the construction, responsible for the lowest natural frequency of vibration.

v. Loadcase 2 (LC2) – Quantifies the stability of the construction, that is, it quantifies the stability factor for a certain structure. The stability factor is defined by the dead load multiplied by the bifurcation factor, *bf*. The bifurcation factor defines the maximum load that can be supported by the structure. For example, if *bf* equals two, then the structure can support a load which is twice its dead load. Each stability factor has an associated *eigenform* that determines the "failure shape" of the structure.

vi. Loadcases 3 (LC3)…, n (LCn) – Quantifies the deformations and oscillations of the construction due to standardized earthquakes. Depending on the direction of vibration, these load cases generate different mode shapes ("eigenform") corresponding to natural frequencies of vibration ("eigenfrequenz"), for the case of a standardized earthquake. Simulations of the structure subjected to standard earthquakes generate the following results: *eigenschwigungsformen* (form resulting from the earthquake oscillation, which can be visuelized with BUILD Animator) of the construction, the *eigenschwingungszeit* (period of oscillation), the associated stresses and induced deformations. Eigenfom, the evaluation of the mode shapes is given by the response spectrum ("*Antwortsspektrum*").

2.3 Structural Performance of Lightweight Structures

After exposing the definition above, it is possible to define structural performance. In this work a good structural performance is the combination of the following factors:

(a) Highest bifurcation (or stability) factor;
(b) Highest load bearing capability
(c) Low stress response spectrum to a certain applied load:
(d) Minimum deformations (strain/displacement)

Additionally, for the lightweight structures, it is desirable to have volume/mass that are as small as possibly allowed by the laws of nature.

3 Structural Analysis

Three existing buildings that make use of tree-like structural columns as the main structural support for the roof loads were selected as case studies:

- *Stuttgart Airport, Germany*
- *Beaverton Library, Oregon, USA,*
- *Therme Bad Oeynhausen, Germany.*

All three buildings have different structural tree typologies and are made of different materials. Structural analysis was carried out using Build software to simulate structural behaviour of the existing base case studies. This will be examined to understand the existing structural behaviour.

Further structural analysis of the base cases was performed to derive the geometrical form in different morphological types and to examine the influence of geometrical criteria, such as complexity, dimensionality proportions, branching angles, symmetry, and multiple branching systems (bifurcated, trifurcated etc).

Materials to be compared for each derived shape are:

- Steel (inorganic material continuous)
- Solid wood (organic, continuous joints)
- Glue-laminated wood (organic, articulated)

3.1 Stuttgart Airport - Germany

The Stuttgart airport is selected for the first case study due to its characteristic tree-like structures, which are unique with their span structure and fascinating geometry. The following is a summary description of the project. Details of the architecture and structure are given in 3.1.1.

Architect:	Gerkan, Mag, and Partners, Hamburg
Draft design:	Meinhard von Gerkan, Karsten Brauer
Structural engineers:	Weidleplan Consulting, Stuttgart.
Checking engineering:	Schleich, Bergermann und Partner SBP gmbh
Structure:	Tubular Steel, twelve tree-like columns support the roof.
Building type:	Airport Building
Period:	1981-91, (planning and construction) .
Map:	

Fig 3.1 Stuttgart Airport, Germany (Satellite Image from Google Earth)

3.1.1 **Architecture**

Architecture may be regarded as national expression. Airports fall under representative architecture and are the first contact of the visitors with a different culture, who will be hosting her/him for the the period of stay. Therefore the design of such buildings should have an exceptional attractive appearance. The case of Stuttgart airport represents a unique design due to the integration of tree-like support structures for the mono-pitched roof. The functional demand is outstandingly met for airport requirements. It offers an ease of orientation and smooth flow of passengers, staff and baggage. The appearance of this airport is characterized by the remarkable roof of the hall. The space serves for baggage pick up and is easy to access, having a great view due to its open space concept. Passengers can easily walk through and find their way.

The most important element is the tree-like structural system that supports the roof. The actual roof surface is divided into twelve equal rectangular sections measuring 26.6 x 43.4 m, erected as a two-way steel section system. Each area is supported by a “steel tree,” outlined by strips of glass, with the loads passing down through the branches to be collected in the tree trunk. The architect mentioned that his inspiration came from the neighbouring Black Forest. Perhaps contemporary architectural trends were also influential. Fritz Leonhardt, one of the world’s foremost designers, said that he was impressed by how the project was handled, but he was sceptical about comparing the structural form to that of a tree; outermost frail branches of living trees are not intended to withstand heavy loads.

Fig 3.2 Stuttgart airport- view from the top of the gallery[5]

“In any case, we are faced with a remarkable piece of man-made landscape architecture”. The slanted roof surface tells us immediately the direction we must take to reach the planes. The tree structures, with their almost Gothic qualities, dominate the space and contrast nicely with the granite floor and terraces. Especially at night, when the powerful uprights literally lift the

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[5] http://en.structurae.de/photos/index.cfm?JS=16766 (2006-09-19)

treetops, the hall emanates a lyrical aura, *"ein dankwürdiges Erlebnis"* (Eggen, P.E., and Sandaker N. B., 1995).

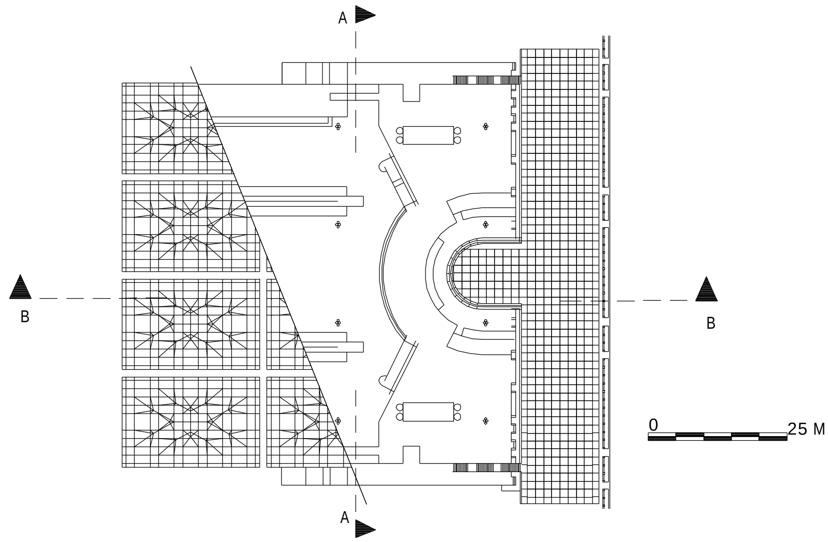

Fig 3.3 Floor plan, Stuttgart Airport

The building is of rectangular shape and the roof is mono-pitched. There are three different levels, whereby tubular tree-like columns are placed on each level forming a cascade and the drop of the roof.

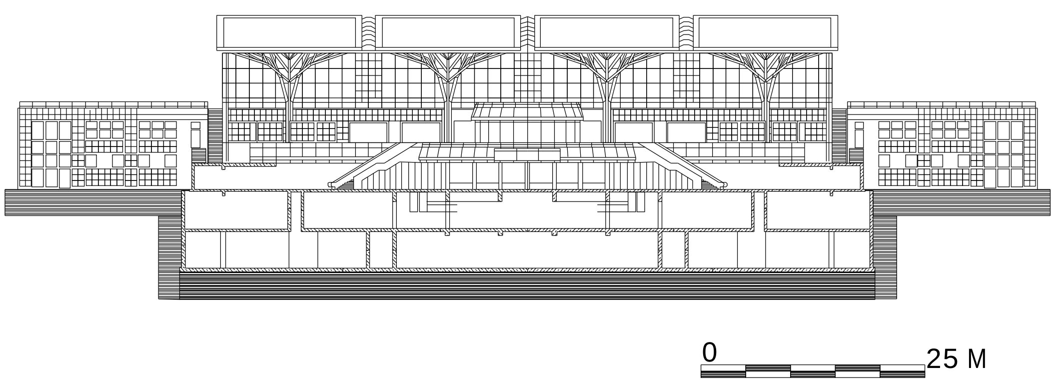

Fig 3.4 Section A-A, Stuttgart Airport

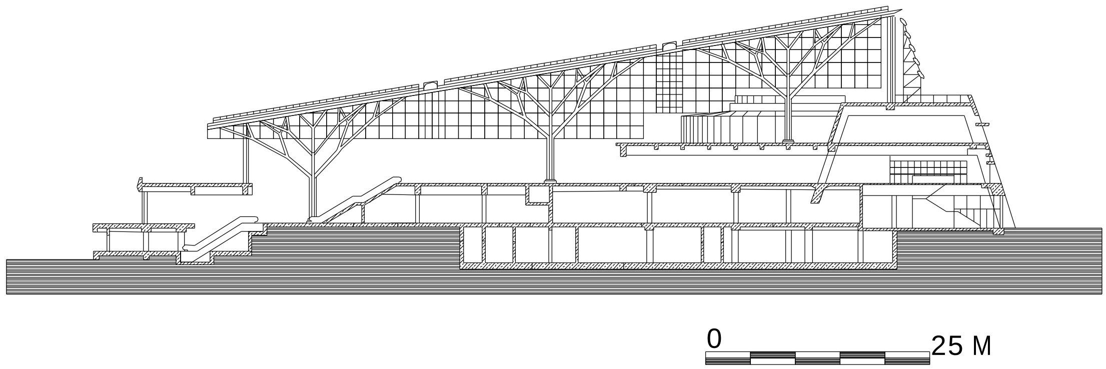

Fig 3.5 Section B-B, Stuttgart Airport

A single support is composed of four tubular poles that are attached to each other and spread to form the tree branching in three different levels (each column forms three branches, with four sub-branches each, to finally support the roof). There are four sets of similar branching systems that repeat themselves up to the roof.

Even though these columns have organic appearance, they are distributed to carry the roof loads in compression with minimal bending moments. The multiple branching systems direct the forces into smaller resultant points until they cluster the resultant on four tubular steel trunks that work as one.

Table 3.1 Cross Sections

Building element	Material	Diameter (mm)	Height (mm)	Width (mm)
Main trunk	Tubular steel	406.4		
Branches	tubular steel	203.2 and159		
Roof grid	steel, box section		340	150

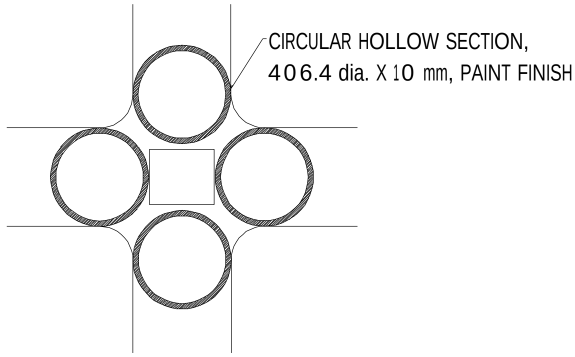

Figure 3.6 Main tubular supports (circular hollow sections) – Stuttgart Airport

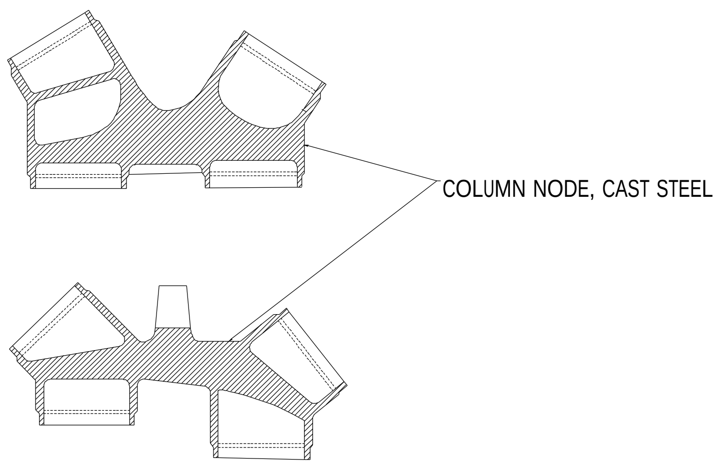

Figure 3.7 Cross sections of the tubular columns nodes made out of cast steel.- Stuttgart Airport.

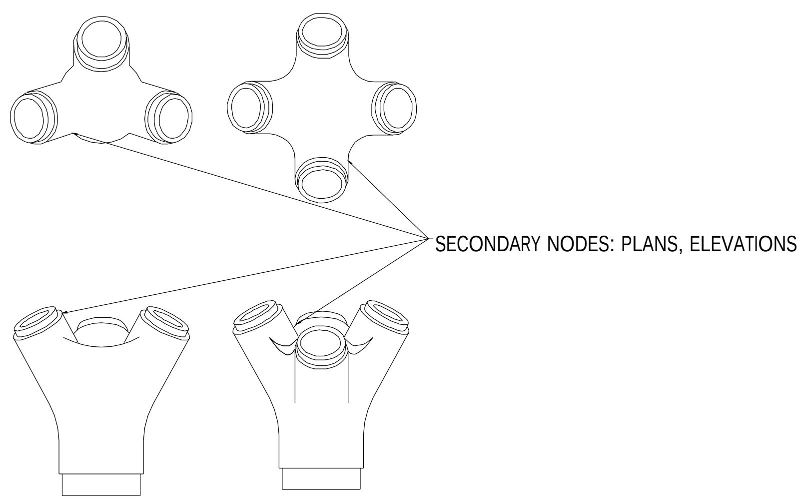

Figure 3.8 Secondary nodes – Stuttgart Airport

The structure comprises twelve umbel columns supporting a beam grid at the roof level. These umbel columns have the advantage of providing closely spaced supports at roof level, while achieving an unobstructed usable area below. The connections between beam grid and columns members are pin-jointed and do not allow movement between these two components. The roof grid junctions are put together using the connecting piece of cast steel material and joined with ‘High Strength Friction Grip Bolts’ (hereinafter referred to as HSFG bolts). There are two types of junctions, one where there is no supporting branch underneath and the other with a supporting branch of 159 mm dia. tube.

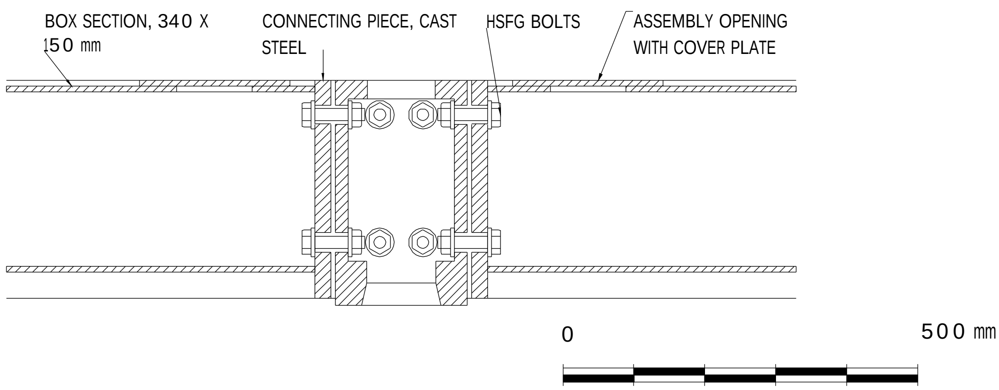

Fig 3.9 Beam junction section

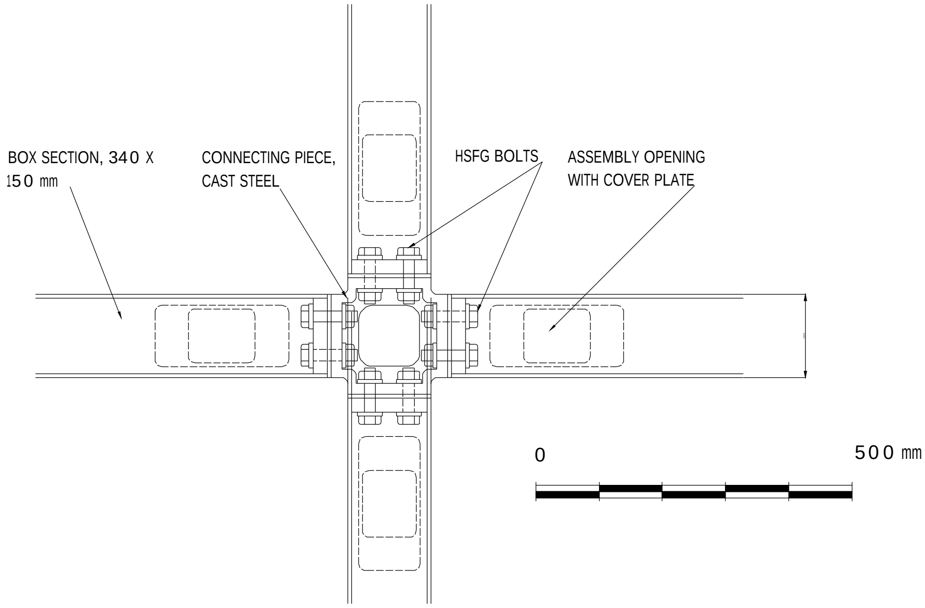

Fig 3.10 Grid junction view from underneath

The following examples illustrate the connection of elements with the supporting branch. The connecting piece of cast steel material is formed as a cross. It is larger than the previous one due to the supporting branch connections to the grid system.

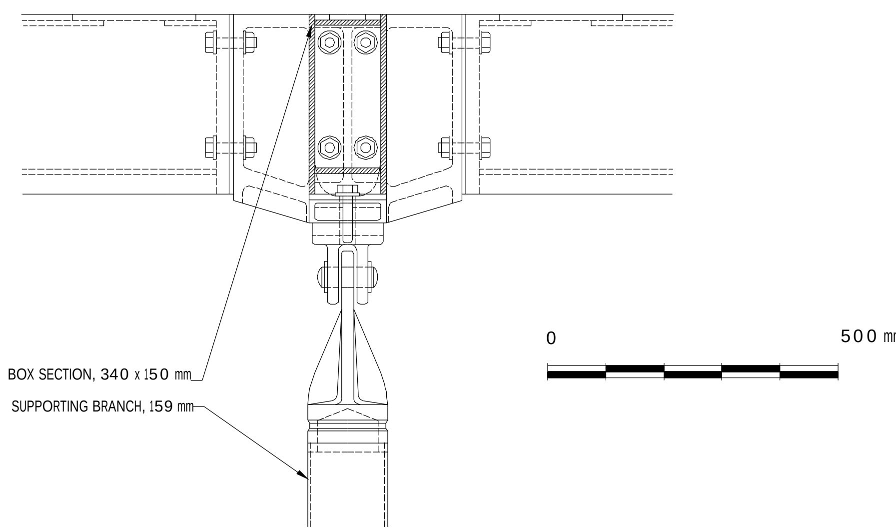

Fig 3.11 Beam grid junction front view

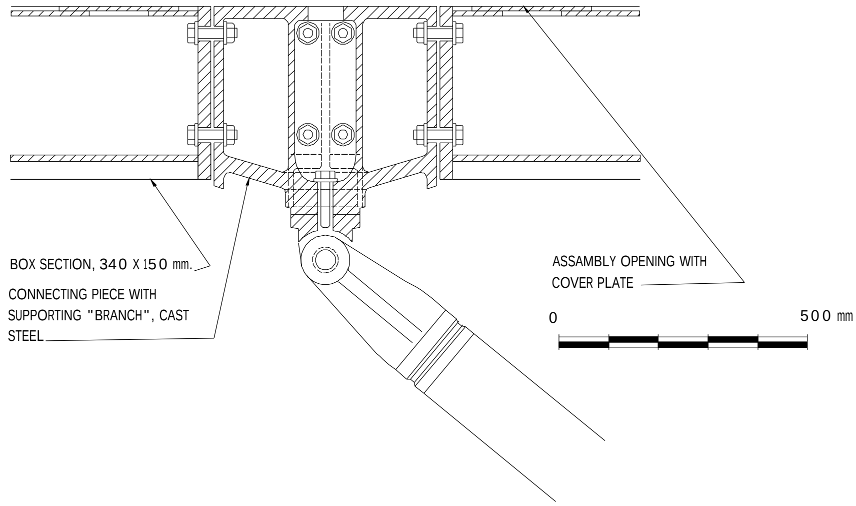

Fig 3.12 Beam grid junction side view.

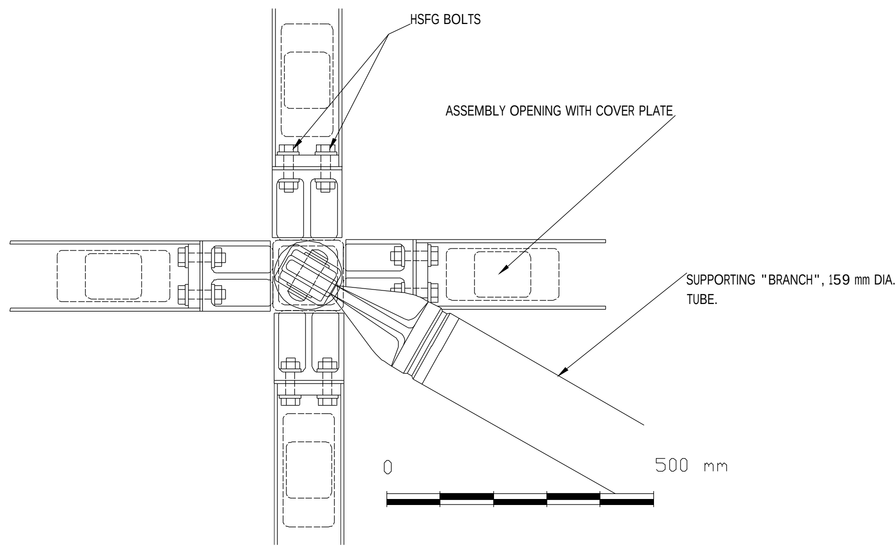

Fig 3.13 Beam grid junction, view from the bottom.

3.1.2 BUILD Model

The Stuttgart Airport construction model consists of twelve units as shown in the Fig. 3.14. The simulation file for the twelve unit model is too big to be simulated with regular computers. The memory of the computer where it was simulated[6] could not support the twelve unit model. The maximum amount of units that could be simulated simultaneously was four units. Six through ten units could be simulated for load case 1 only (without computing the stability factor and earthquake effect).

[6] Acer Intel Pentium M 1.6 GHz, 1 G Ram Memory.

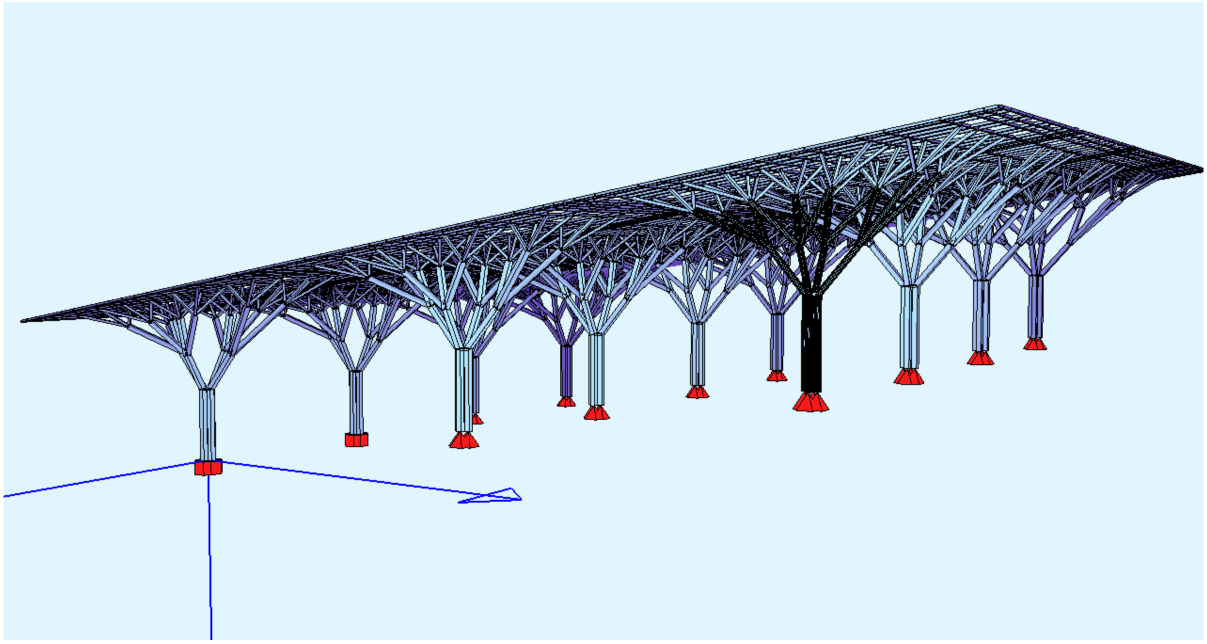

Figure 3.14 Stuttgart Airport BUILD Model.

For the purpose of simplifying the model, two units were chosen for simulation. This was done also to have reasonable computing times, and better visualization of local stresses. One of the corners of the two unit model is anchored, to simulate the link to the remaining structure (see fig 3-15).

3.1.3 Structural Simulation Analysis

The results of structural simulation for Stuttgart Airport are presented in the table 3.2.

Table 3.2 Presentation of results for simulation of tubular steel structure –Stuttgart Airport

Steel								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.678	111.87	0.098					
LC2					43.879			
LC3	0.036	5.9	0.005	1.214				
LC4	0.014	2.34	0.003	0.471				
LC5	0.018	3.04	0.002	0.421				
Model Parameters						12.383	7850	97206.55

The following figure 3.15 is a screenshot from BUILD program. The BUILD program performs visualization of different loads applied to structures. The fig 3.15 presents the relative stress *•/fc* applied to the Stuttgart Airport structure. The Screenshot fig. 3.15

represents spatial animation with genuine cross sections and colours depending on materials applied. For the individual load cases, the deformation can be simulated at the surface of the element, and is represented by a colour scale showing the intensity of the relative stress (Dobivisek, B., 2002, p 6).

In this figure the relative stress applied to the structure (0,678 s/*fc*) shows that the deformation of the material is less than the maximum admissible stress, *fc* (*Pa or N/m*^{2}). The simulation of the load case 1 shows that the structure is stable. The displacement in the structure is 0,098 *m*.

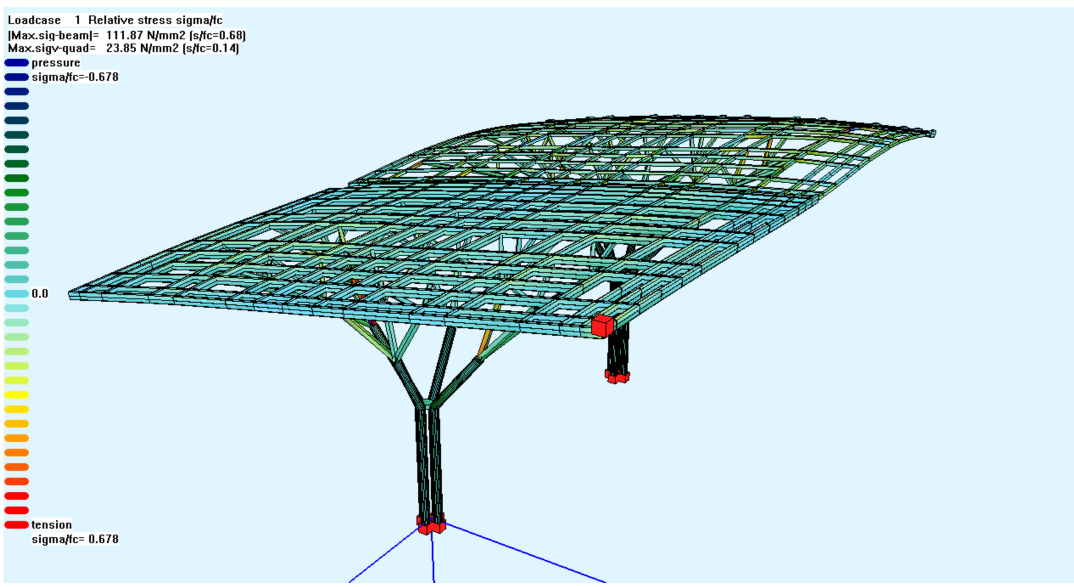

Fig 3.15 Visualization of the stresses applied to the Stuttgart Airport structure (simplified two unit model).

Fig 3.16 is another screenshot taken from BUILD program, to illustrate the structural form resulting from the application of the stability factor (load case 2). The stability factor defines how many times the structure can support its own dead load, which in this case is 43.879 times its own dead load (4,265,326.2 kg). The spatial deformations induced are visualized in the following screenshot, fig 3.16.

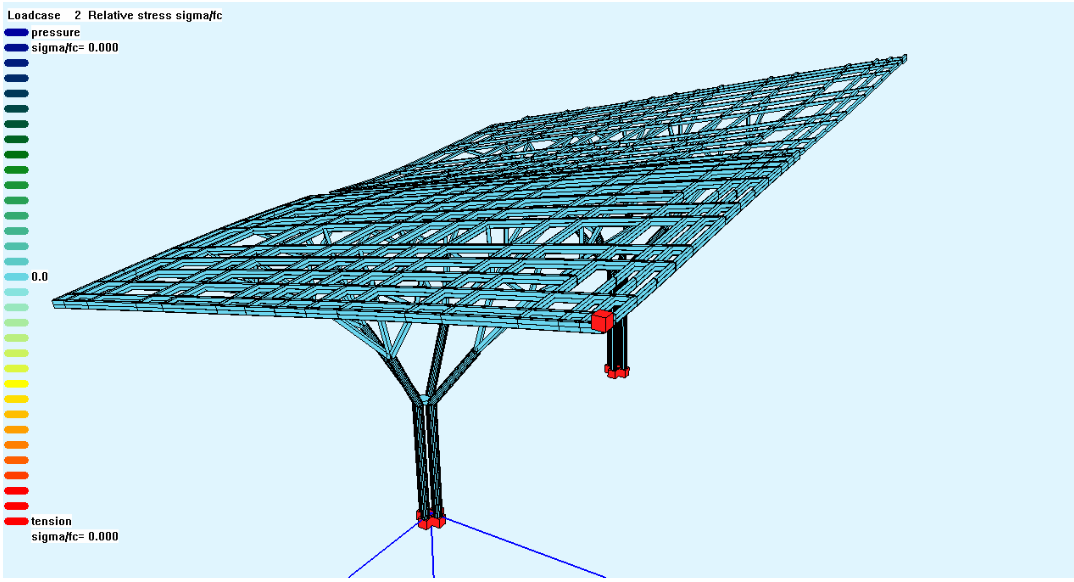

Fig 3.16 Visualization of the stability factor (load case 2), Stuttgart Airport

The load cases 3 to 5 show the deformation of the construction due to standardized earthquakes based on predefined magnitudes taken from the BUILD program database. These load cases will generate different mode shapes. Figs 3.17, 3.18, and 3.19 have different relative stress results and therefore different deformations depending on the magnitude of the earthquake.

Simulation results on fig 3.17 show that a load applied to the structure due to an earthquake is 0.036 and the displacement is 0.005 m. Relative stress due to earthquakes can be seen all throughout the structure in different colours depending on the intensity of the stress and tension applied to the structural elements.

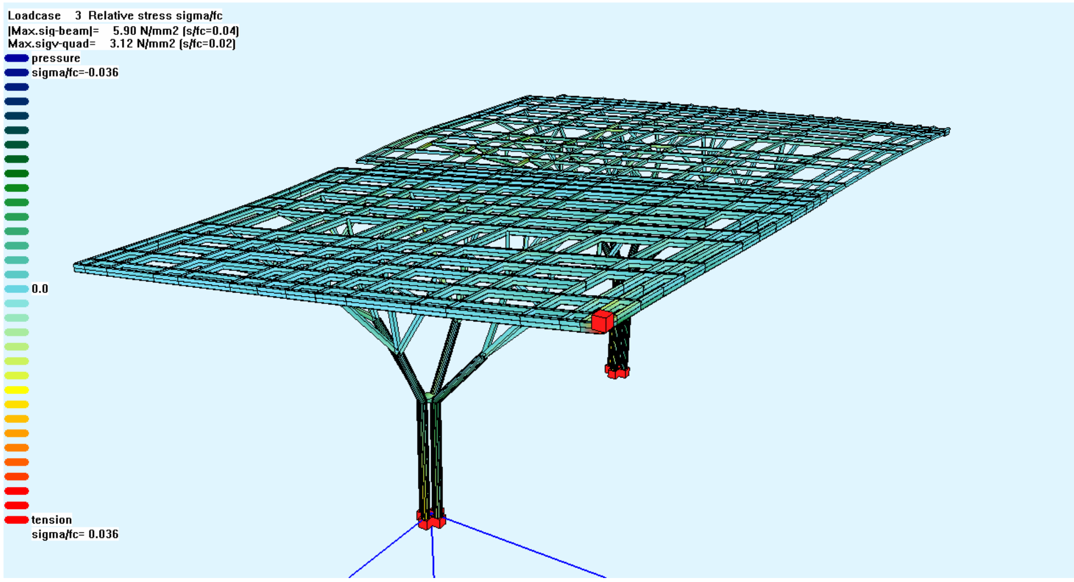

Fig 3.17 Visualization of the stresses induced by load case 3, Stuttgart Airport.

The following screenshot, fig 3.18, shows the result of 0.014 due to earthquake. In this screenshot it can be observed that the displacements are different compared to load case 3, 0.003 meters. This difference depends on the different direction of vibration for the case of standardized earthquake as predefined in BUILD. The part of the structural grid which is not anchored shows a greater deformation (red colour). However these displacements can be neglected since they are only 0.003 meters and therefore the simulation of the structure shows great structural durability to earthquakes.

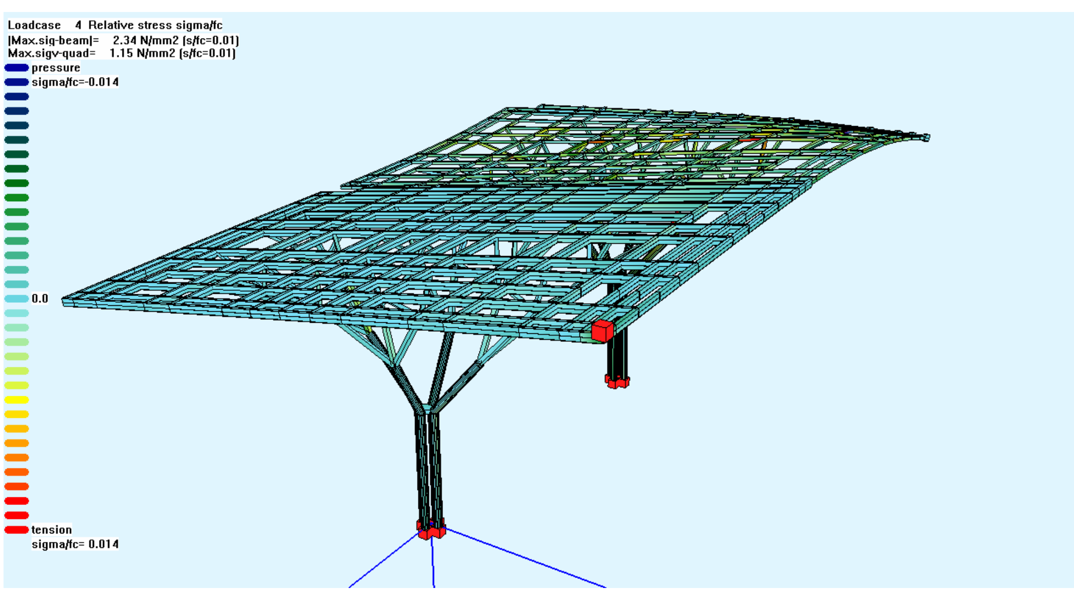

Fig 3.18 Visualization of the stresses induced by load case 4, Stuttgart Airport.

Fig 3.19 shows completely different deformations due to different vibration directions. Yet, the simulation shows that these deformations are even smaller compared to the previous load case 4, 0.002 m. The relative stress given from the load case 5, 0.018 is exceptionally low and the structure is exceptionally resistant to earthquakes.

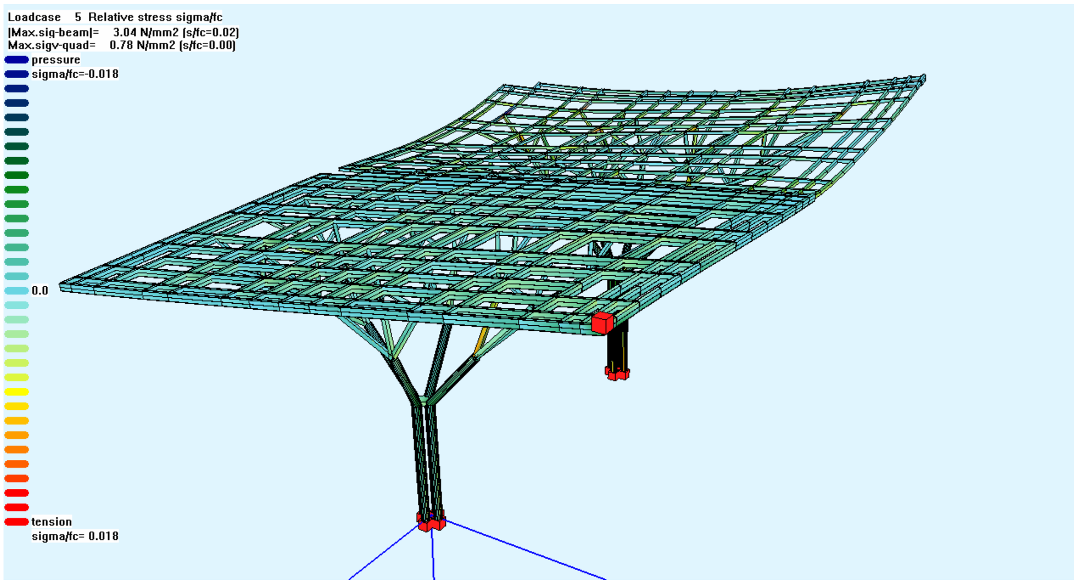

Fig 3.19 Visualization of the stresses induced by load case 5, Stuttgart Airport.

3.2 *Beaverton Library- Oregon, USA*

The Beaverton Library is the second selected case study. This building has characteristic tree-like structures made out of glulam. It shows very elegant with the tree-like structures. The following is a summary description of the project. Details of the architecture and structure are given in 3.2.1.

Owner:	City of Beaverton, Oregon, USA
Architect:	Thomas Hacker Architects Inc., Portland, Oregon
Structural Engineering:	KPFF Consulting Engineers, Portland Oregon
General Contractor:	KPFF Consulting Engineers, Portland Oregon
Landscape Architect:	Walker Macy
Building Size:	641 Square Meters
Building type:	Library
Map:	

Fig 3.20 Beaverton City Library Location (*Satellite image from Google Earth)*

3.2.1 **Architecture**

The Beaverton City Library uses a "forest" of glulam tree-like structures in its design. The building is viewed as a key element in the development of the city's new urban centre (APA-The Engineered Wood Association, 2001). The Beaverton City Library's structural system makes use of four curved glulam columns fabricated to create the appearance of a 7.62 meter tall tree. There are a total of sixteen tree-like columns supporting a Douglas-fir ceiling[7] above the library's main room.

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[7] http://www.midwestlumberinc.com/firpattern.htm (2006-09-10) *Midwest Lumber stocks popular fir flooring and ceiling patterns.*

During the design phase, project manager David Shelman stated, "Once the design metaphor of the trees was decided upon, the design team looked at several options to achieve the look of large, curved beams to create the trees. (…) Using glulam fabrication with thin laminations achieved all of the required structural properties while representing a solid member appearance"[8].

The central library incorporates electronic networking capabilities and illuminated open spaces for reading and browsing. The two storey building includes an auditorium with a capacity of 150 seats, public meeting rooms, a personal computer room and a large children's area. Located in the city centre, the library plays a double role of community and information resource centre.

Fig 3.21 Beaverton City Library (*Canadian Wood Council)*[9]

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[8] 2001 APA-The Engineered Wood Association: "*Beaverton City Library: A Forest of Glulam. Case Study*"

[9] http://www.cwc.ca/design/architectural/projects/Beaverton/index.php (2006-09-10)

The building was renovated and completed in September 2000. The new library provides more than triple the space of the previous building and is one of the busiest libraries of its size in the country.

A pre-cast concrete hollow core plank floor supported on a pre-cast concrete girder, as well as a combination of pre-cast concrete and concrete masonry piers serve as the structure for the first two floors. The system satisfied the need of high live load capacity, large open spaces and an ordered modular building grid.

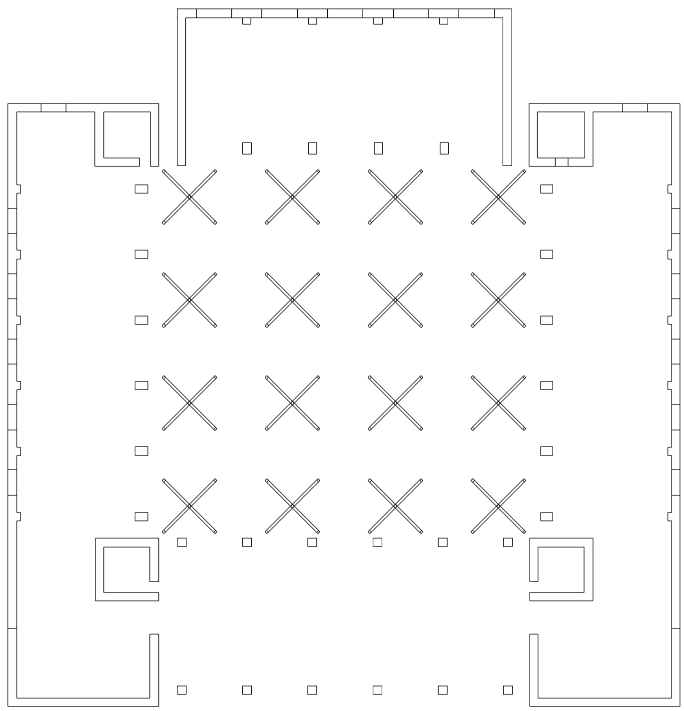


Fig 3.22 Beaverton City Library floor plan

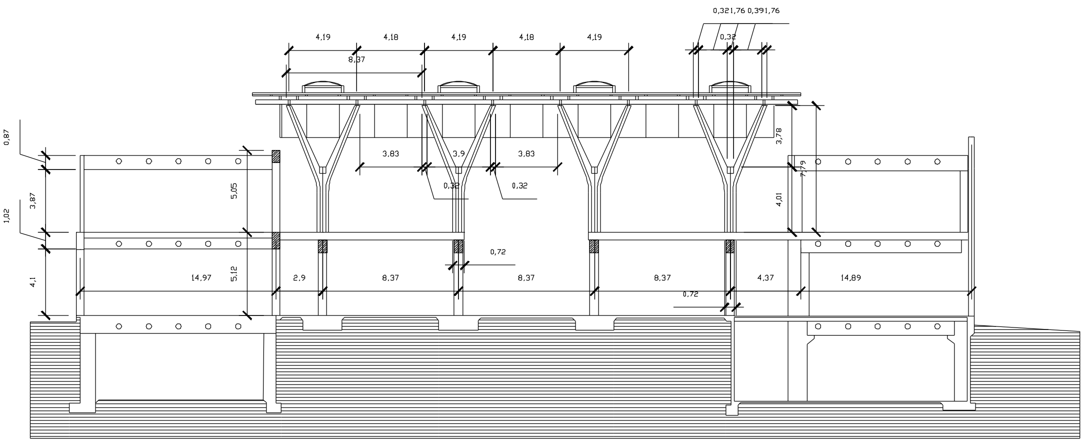


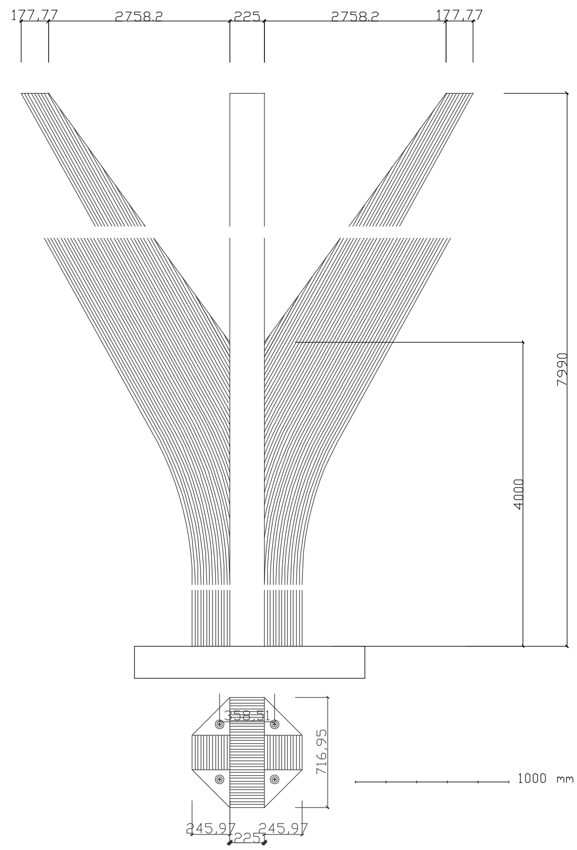
Fig 3.23 Section of Beaverton Library – the tree-like structure emerge only on the second floor.

Sixteen glue-laminated columns rise 7.62 meters from the second floor. Each column consists of four curved 2.25 cm wide glue-laminated sections that are tapered in depth from the mid-height curve to the top of the member. At the base columns are cruciform shaped, with each section bolted to a pedestal with blind mortised steel plate connections[10]. The tree-like columns are made of 1.9 cm laminations of Douglas-fir lumber, which is half the thickness of regular laminate pieces, to achieve the required radius of curvature[11].

[10] Spotlight Structure Magazine, March 2006

[11] 2001 APA-The Engineered Wood Association "*Beaverton City Library: A Forest of Glulam. Case Study*"

The cross sections of the Beaverton Library are represented in table 3.3 and corresponding diagrams in Fig. 3.20 to



3.22.

Fig 3.24 View of the tree-like support – Beaverton Library

Table 3.3 Dimension of the Beaverton Library structural elements.

Building element	Material	Width (mm)	Length (mm)
Main vertical support (cross section, cs1b)	Glue-Laminated wood	225	717.5
Second main vertical support (cross section, cs2b)	Glue-laminated wood	225	247
Tree branches (cross section at start, cs3b)	Glue-laminated wood	225	1560
Tree branches (cross section at end, cs3b)	Glue-laminated wood	225	177
Rafters (cross section at end, cs4b)		177	304

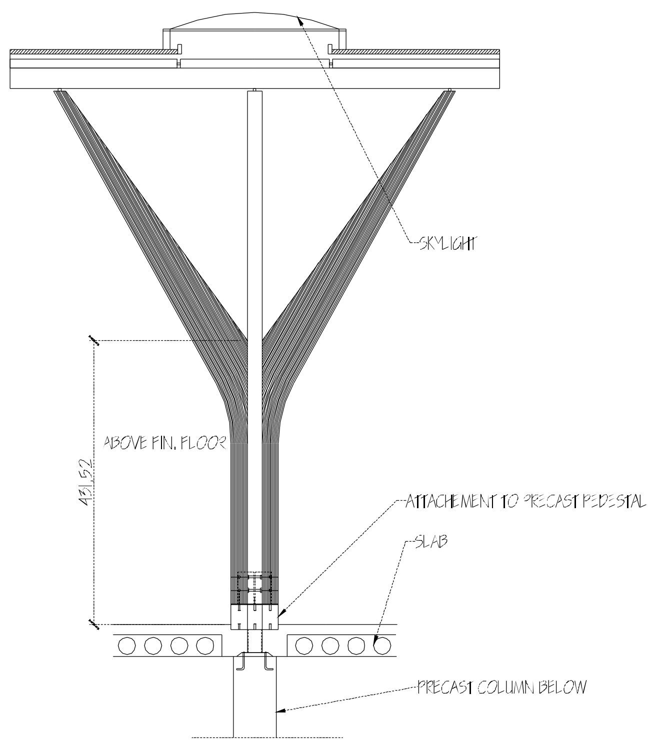


Fig 3.25 Detailed section – Beaverton Library

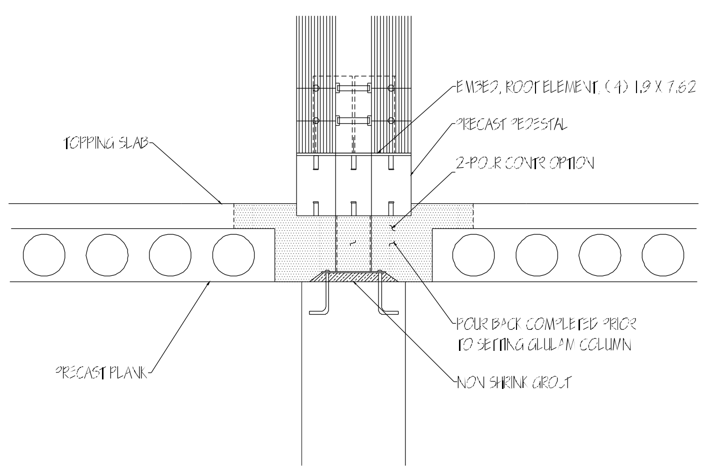


Fig 3.26 Connection of the column into the slab- Beaverton Library

3.2.2 **Build Model**

The Beaverton Library model comprises of 16 tree-like units as shown in fig 3.27. Although the complete model can be simulated with the computer available for this purpose, for simplification purposes and to better visualize the results, a simplified four unit model is selected. The simulation results for the load case 1 and 2 are equivalent for both models, which means that the simplified model is a good representation of the real structural performance.

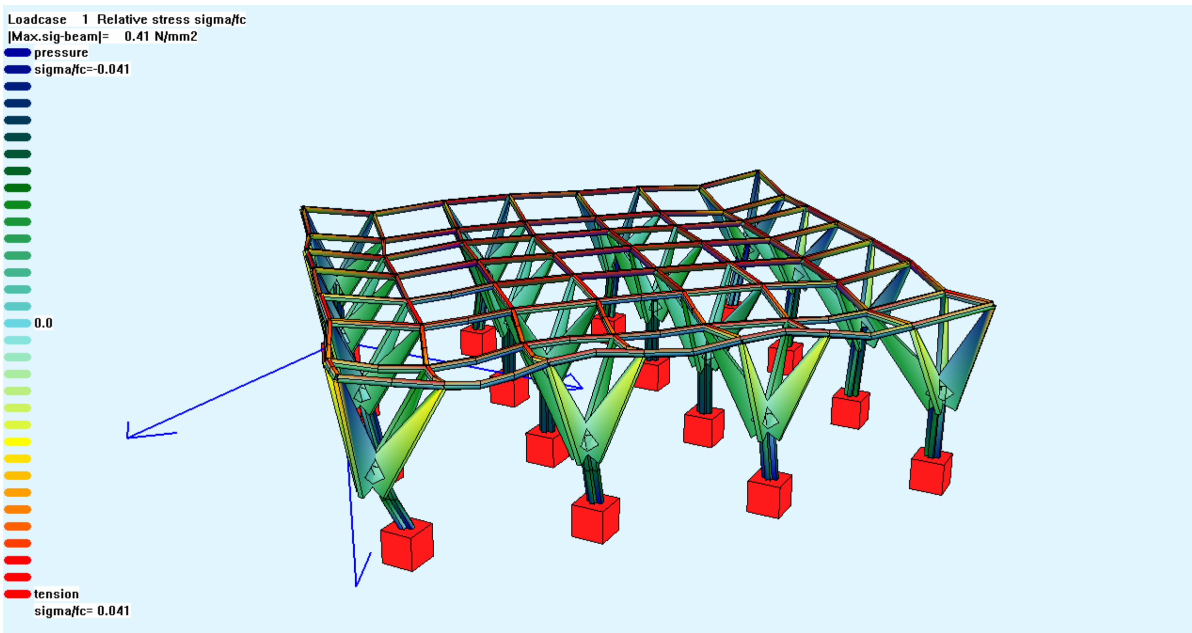


Figure 3.27 Beaverton Library (16 tree-like units simulation)

3.2.3 **Structural Simulation Analysis**

The following table summarizes the structural simulation results for Beaverton Library. The relative stress induced by each load case is insignificant, the highest value being of the order of 7% of *fc*. The bifurcation or stability factor of 277 is another indicator of stability of the structure.

Table 3.4 Presentation of simulation results for wood – Beaverton Library

Wood								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m^3)**	**Weight, kg**
LC1	0.042	0.42	0.000					
LC2					277.361			
LC3	0.07	0.7	0.003	0.437				
LC4	0	0	0	0.371				
LC5	0.047	0.47	0.002	0.343				
MODEL PARAMETERS						27.384	800	21907.2

The fig 3.27 is a screenshot from BUILD program, where the relative stress applied to Beaverton Library structure can be visualized. In this particular screenshot, we can have a better understanding of the simulation results: the change of colour gradation represents different degrees of strain, in relation to different locations of the structural elements.

It can be observed that the structural timber grid is subjected to considerable tension (red colour). The relative stress is very low, only 0.042, whereas displacements are 0 meters. The "Build" structural analysis results illustrate that the glue laminated wood structure has good structural performance.

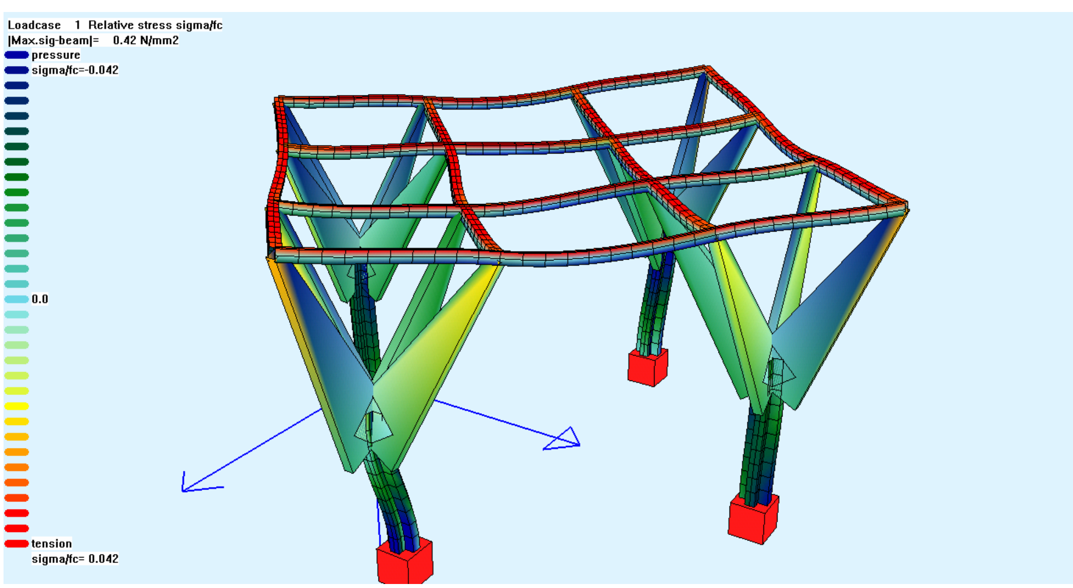


Fig 3.28 Visualization of the stresses applied to the Beaverton Library structure under the sole influence of the dead load.

This screenshot illustrates the result of the stability factor (load case 2) for Beaverton Library structure. This structure can support its own dead load 277.36 times, or a total of 6,076,202.9 kg, or 38,517 kg per square meter.

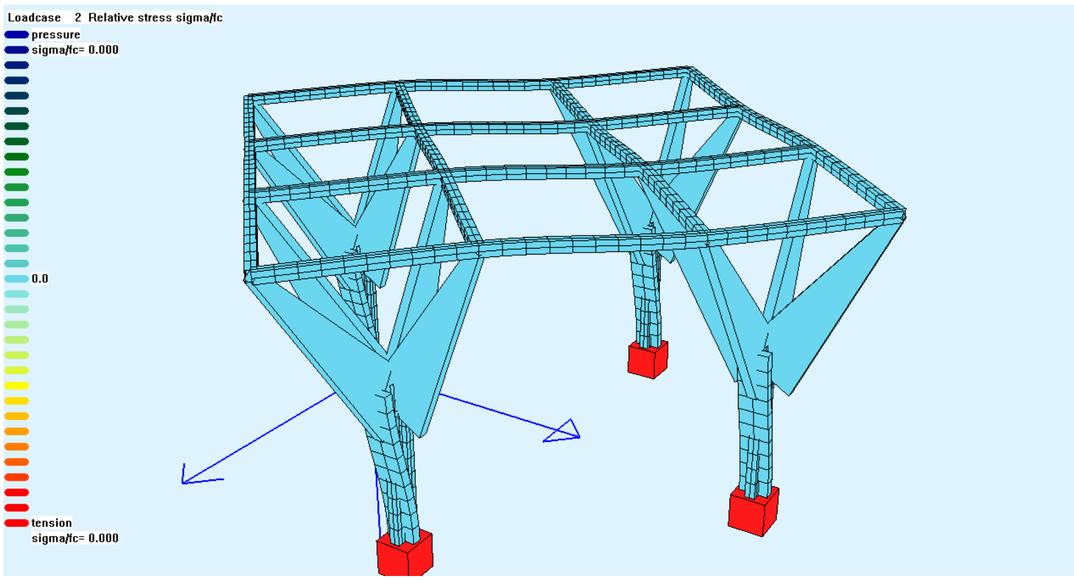


Fig 3.29 Visualization of the stability factor (load case 2), Beaverton Library.

The following screenshots, fig 3.29, 3.30, and 3.31 represent the load cases (3, 4, and 5) as a result of standardized earthquakes. The relative stress resulting from the earthquake on load case 3, fig 3.29 is relatively low, 0.07 s/*fc*, and the displacement is only 0.003 m.

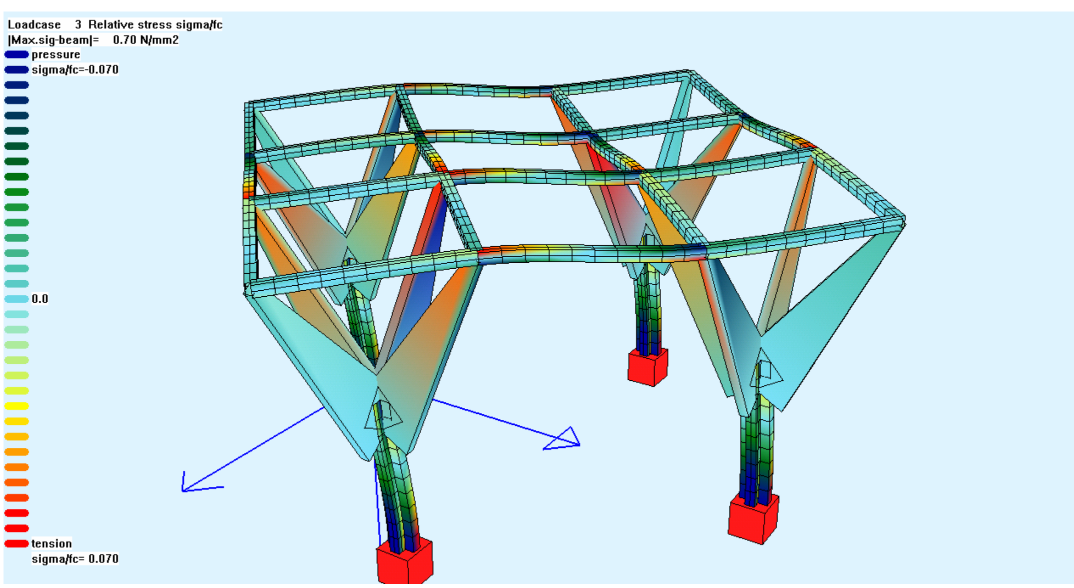


Fig 3.30 Visualization of the stresses induced by load case 3, Beaverton Library.

The following screenshot, fig 3.30, illustrates that the relative stress is zero, however on the screenshot it can be observed that the constructions is still under strain. This visualization could be performed better by using other rendering programs rather than BUILD.

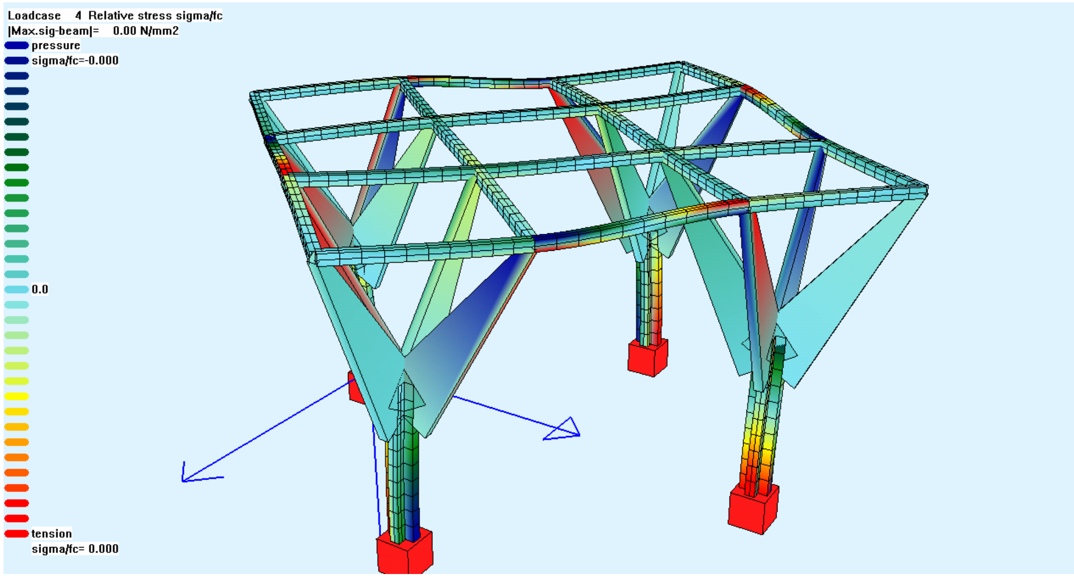


Fig 3.31 Visualization of the stresses induced by load case 4, Beaverton Library

The screenshot, fig 3.31 shows different deformations due to the different vibration directions. The simulation shows that the displacement is lower compared to the previous load case 3, 0.002 meters and insignificant considering the magnitude of the deformation. The relative stress given for the load case 5, 0.047 s/*fc* is very low and the structure is exceptionally resistant to the earthquakes.

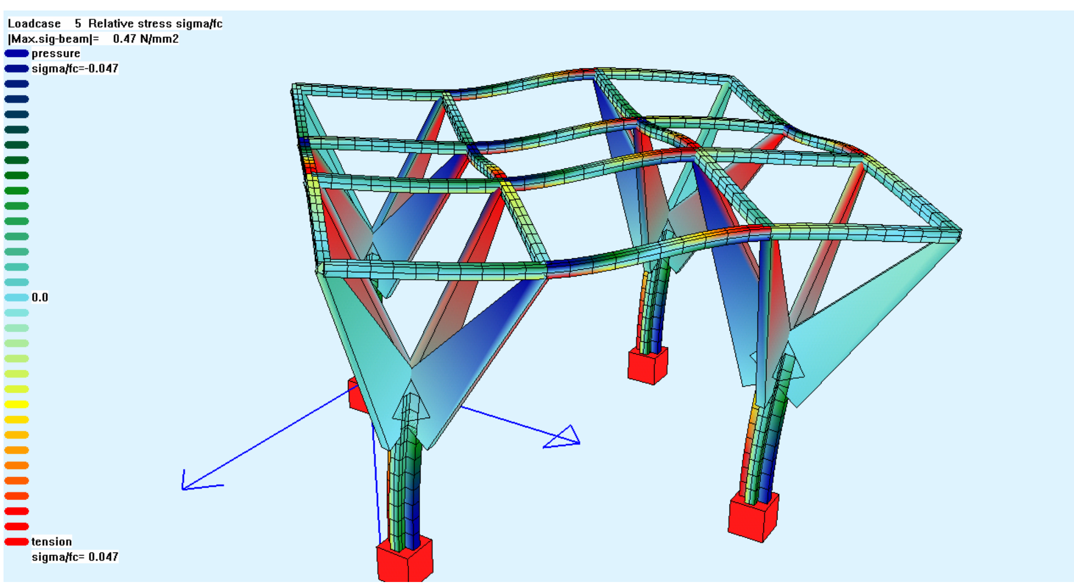


Fig 3.32 Visualization of the stresses induced by load case 5, Beaverton Library

3.3 Therme Bad Oeynhausen – Germany

The Therme Bad Oeynhausen is the third selected case study. It is a single story structure arranged in circular form and it supports the gable roof slopping downward into two parts. This is the only case where the main support structure is composed of two different materials. The concrete column is the main support where the tree-like branches are clustered. The following is a summary description of the project. Details of the architecture and structure are given in 3.3.1.

Location:	Oeynhausen Germany,
Architect:	D.I. Heiner Maria Sommer, National Board of Works Düesseldorf III.
Structural Engineering:	Brüninghoff, Rampf
General Contractor:	MBN Montage-Bau GmbH & Planungsbüro Rohling
Building Size:	6,120 Gross Square Meters
Building type:	Spa
Initial Planning:	February 1994
Construction Start:	April 1994
Construction End:	October 1995

3.3.1 **Architecture**

The construction work was performed on the existing Spa (*Wittekind-Therme*), located in the middle of the Bad Oeynhausen Park. The aim of the project was the harmonious integration of natural construction elements and materials in the existing building infrastructure with minimal intervention in the main construction and in the surrounding green park area. The new form encompasses the existing construction and develops at the same time a new bathing landscape with diverse healing and adventure potentials.

The visual link between the green areas of the thermal park and the inner *Bali-Therme* was achieved through the large glazed surface on the east façade.

Fig 3.33 Indoor view of the Balitherme, Bad Oeynhausen[12]

The ground floor of the spa is completed with reinforced concrete. The structure is composed of concrete columns and wood glue for wing units as well as the rafters and timber battens. The roof is composed of glue wood supported by rafter and a timber formwork (Prosnez A., 2003). It supports the cover wooden wool panels. The opaque part of the roof is covered with zinc plates.

Reinforced concrete columns support timber branches and form tree-like columns. The single-storey structure is arranged in circular form. Altogether, a total of 13 axes group themselves over a central point, forming an external radius of almost 40 m (equivalent to the external building envelope).

The wood span structure is held by reinforced concrete supports in a circular geometry. The spanning width of the structure is 6.4 – 13.17 m; the room heights are 4.8 – 8.2 m.

The tree-like branches spreading out of concrete columns and the segmented acrylic glass ceiling transmit the sensation of a generous, open space.

[12] http://www.mercure-oeynhausen-city.de/images/balitherme2.jpg

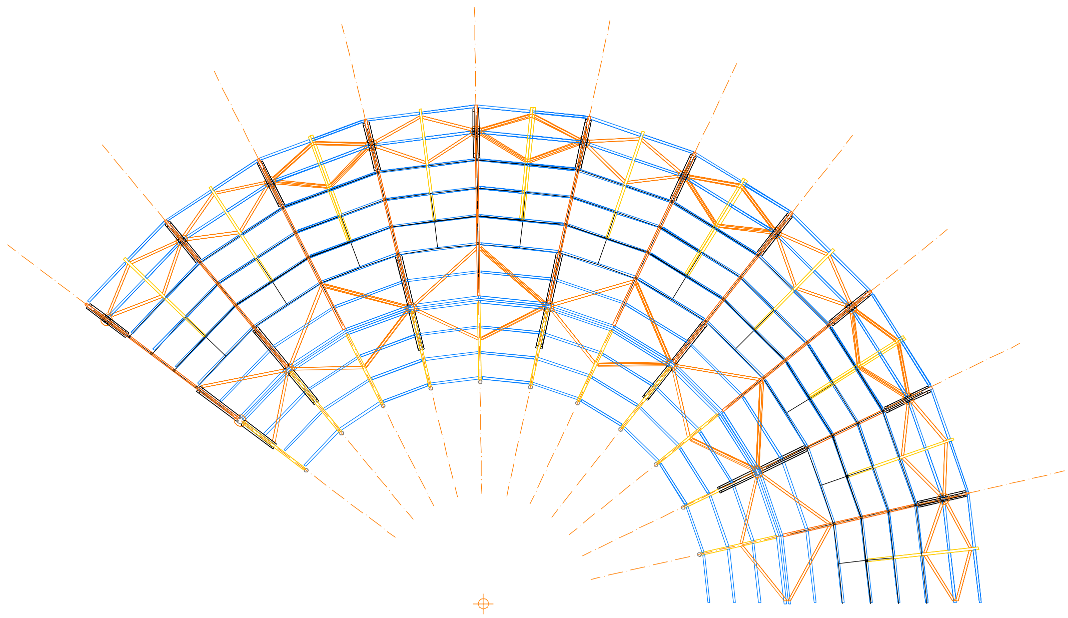


Fig 3.34 Structural floor plan

The internal building envelope (internal radius) is approximately 17.3 m. The circular tree-like structure is extended over 143°.

Circular segments and *rotundas*, wood and glass construction, natural materials with open-pore structures, such as the ceiling rendering made of fibro-acoustic and the natural colours integrate the *Bali-Therm* in the surrounding landscape. The building is designed in a friendly manner for the handicapped. The aesthetics of the construction is influenced by Indonesian architecture. The external facilities with natural formed water surfaces, stones, bridges and plants enable an optical connection to the thermal park.

The tree-like structure of the spa is a combination of different timber sizes (rafters, and timber battens) that shape the main support of the roof. The set of cross sections is as follows:

Table 3.5 Cross sections, Therme Bad Oeynhausen

Material/Profile	Diameter (cm)	Length (cm)	Width (cm)
Rafter 1		14	14
Rafter 2		14	23
Rafter 3		18	43
Concrete column 1	50 ϕ		
Concrete column 2	30 ϕ		

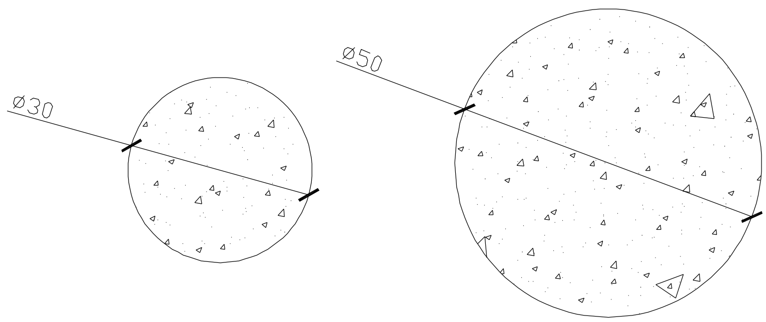


Figure 3.35 Concrete columns cross sections.

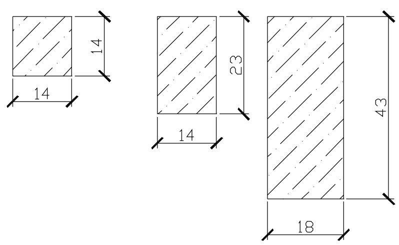


Figure 3.36 Rafter cross sections - profiles

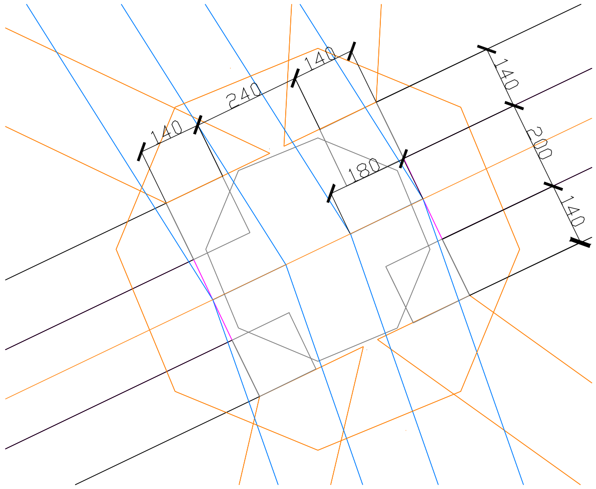


Fig 3.37 Rafter junction detail, link to the concrete column.

3.3.2 **Structural Simulation Analysis**

The following table shows the results for Therme Bad Oeynhausen.

Table 3.6 Presentation of simulation results for Concrete-Wood-Steel Cable

Concrete-Wood-Steel Cable								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm²)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m³)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.358	5.58	0.003					
LC2					159.994			
LC3	0.048	0.48	0.001	0.279				
LC4	0.041	0.41	0.001	0.252				
LC5	0.052	0.52	0.001	0.246				
Model Parameters (Concrete)						15.365	2500	38412.5
Model Paremeters (Wood)						123.43	800	98744

Fig 3.38 is a screenshot from BUILD program presenting the applied to Therme Bad Oeynhausen structure. It can be observed that the tension is greater on the rafters in the centre of the structure. However, the relative stress of 0,358 is within the acceptable limit (less than 1), and the deflection is 3 millimetres. Based on these data and on the high stability factor (159.99), we can conclude that the structure is stable.

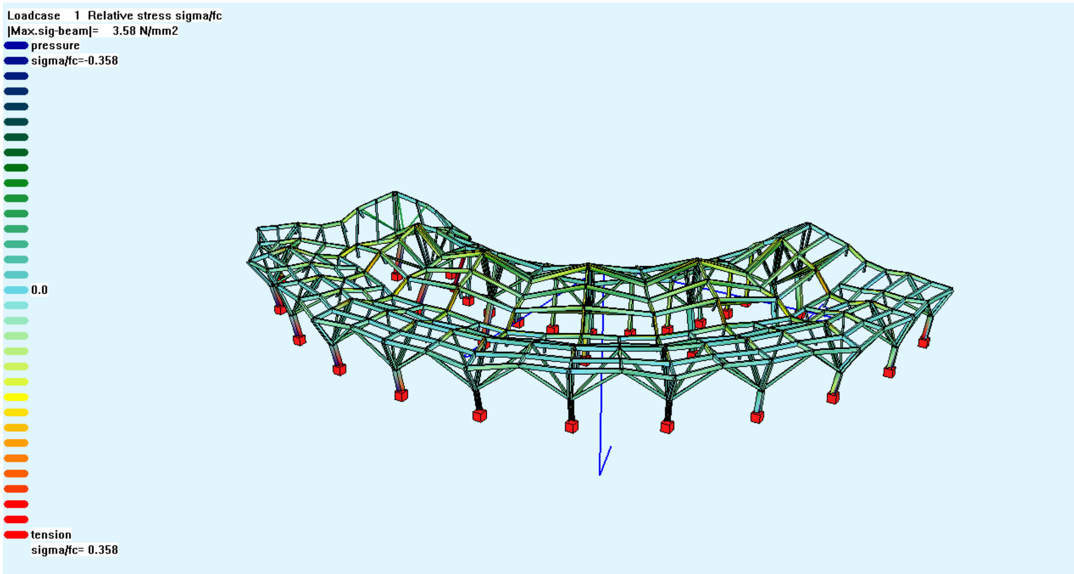


Fig 3.38 Visualization of the stresses induced by load case 1, Therme Bad Oeynhausen.

Fig 3.38 illustrates the stability factor (load case 2) for Therme Bad Oeynhausen. The stability factor in this case is 159.99 times of its own dead load (137,156.5 kg x 159.99), or a total of 14,352.73 kg per square meter.

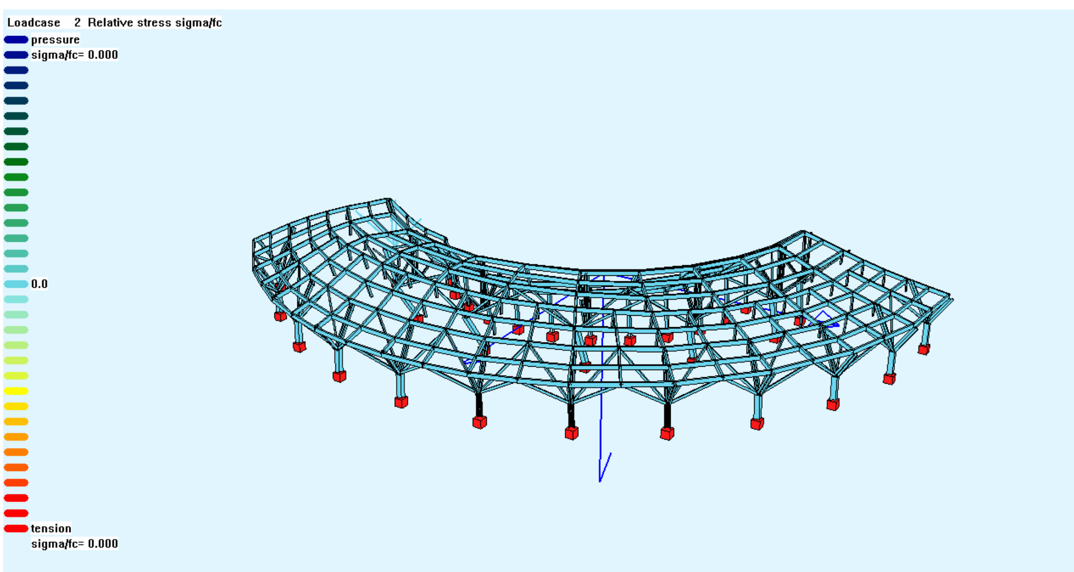


Fig 3.39 Visualization of the stresses induced by load case 2, Therme Bad Oeynhausen

Fig 3.39 quantifies the deformations and oscillations of the construction due to earthquake. It can be noticed that the centre of the structure is on tension and that some minor deformations there are expected, given that the relative stress relevant to this load case 3 is 0.048 s/*fc* that is of lower-grade. The displacements expected are very small, in the order of 1mm..

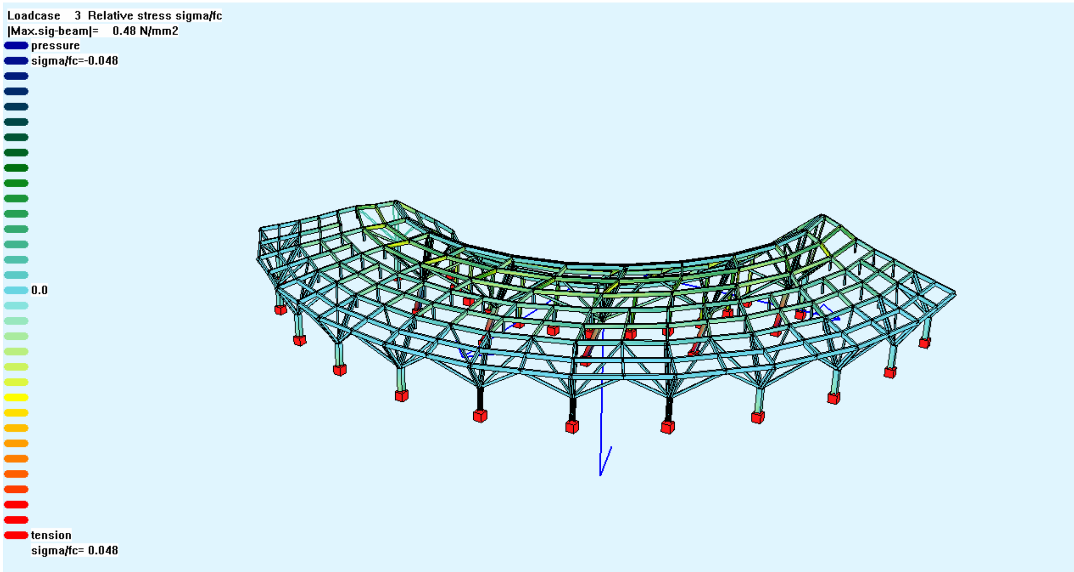


Fig 3.40 Visualization of the stresses induced by load case 3, Therme Bad Oeynhausen

The next screenshot, fig 3.40 illustrates also deformations and oscillations of the construction due to earthquake. It can be observed that on the left side of the structure, the deformations are greater than the rest of the construction. This happens due to the vibration direction that generates a different mode shape; therefore since the shape of the structure is circular from 0 to 143 degree, the location of this deformation coincides with the direction of the earthquake impact. On the other hand, the relative stress for this load case 4 is of much of lower grade than the elastic module, thus the displacements in this case are low too, 0.001 meters.

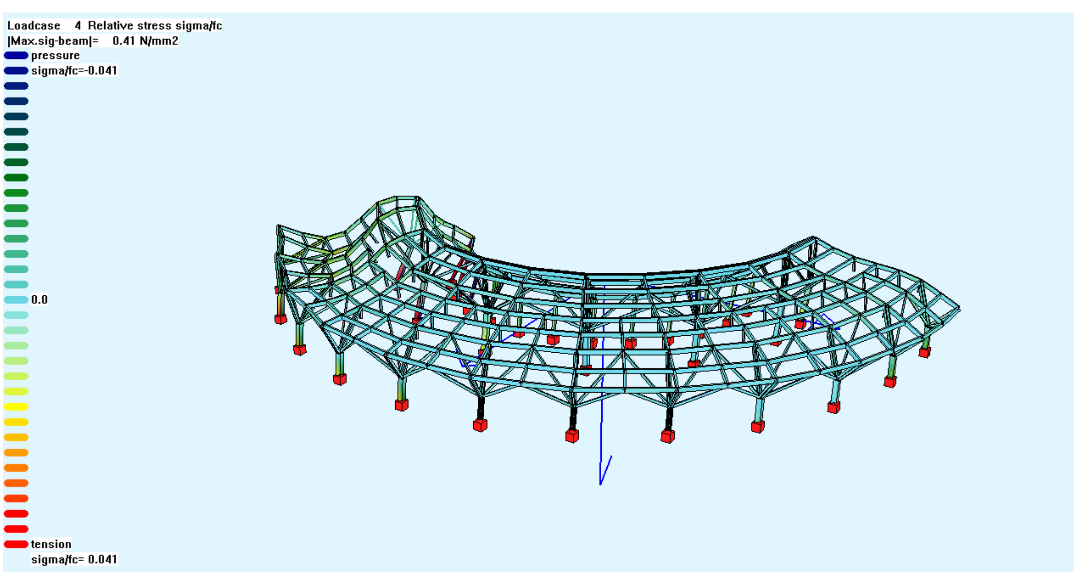


Fig 3.41 Visualization of the stresses induced by load case 4, Therme Bad Oeynhausen

The next screenshot, fig 3.41 is the result of the deformations and oscillations of the construction due to an earthquake with higher natural frequency, associated to load case 5, as pre-defined by BUILD. In this case the right side of the rafters is subject to greater deformation than the rest of the construction. This also happens due to the different vibration direction that generates different mode shapes. Therefore as mentioned before, due to the circular shape of the structure, the right side of the rafters is on greater tension. However, very low displacements are expected again in the order of 1 mm.

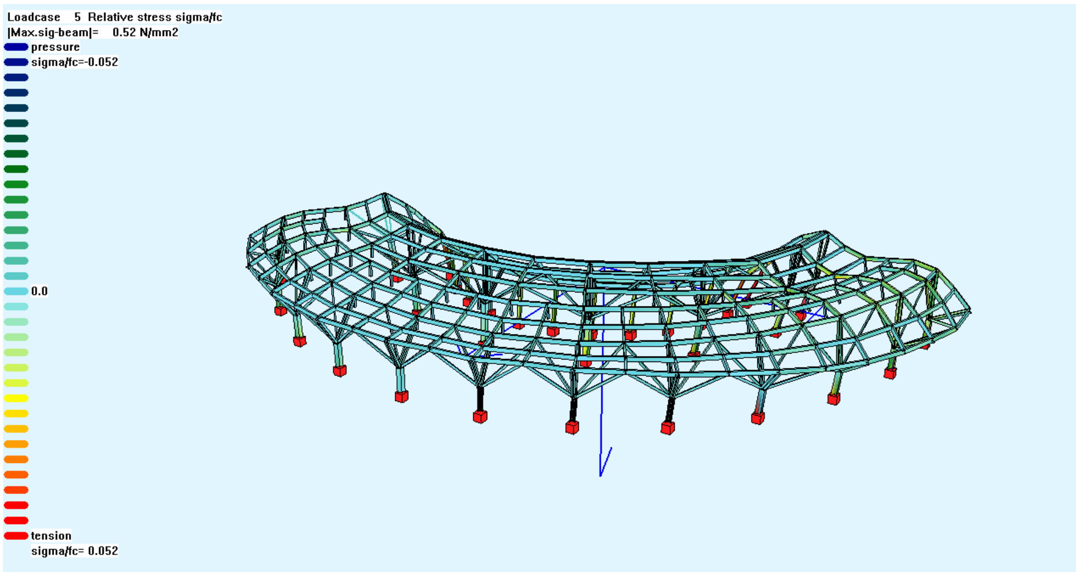


Fig 3.42 Visualization of the stresses induced by load case 5, Therme Bad Oeynhausen

4 A Comparative Structural Analysis

The shapes adopted for structural elements are affected, to a large extent, by the nature of the materials of which they are made. The physical properties of the materials determine the types of internal forces, which they can sustain and, therefore, the types of structural elements for which they are suitable. In the case of tree-like structures, the physical properties of materials will be explored and composed for a base set of structural component types.

Structures must be capable of achieving a state of equilibrium under the action of the applied load (Agnus Macdonald 2001, p9). Therefore, it is expected that geometric stability is the property which preserves the geometry of structure and allows its elements to act together to resist load (Agnus Macdonald 2001, p9).

In this chapter, the structural differences of the above case studies will be examined. Different cross sections and materials will be introduced to the existing morphology to investigate its structural behaviour. The best structural performance is defined as the maximum load bearing capacity of the lightweight structure to the point of failure. It is a way of determining the ability of a structure or any of its constituent members to safely carry a given set of loads without material distress or excessive deformation given the arrangement, shape and dimension of members, the types of connections and supports utilized and the allowable stress of the materials employed.

The structure must be strong enough to resist the worst loading conditions scenario without collapsing, while, at the same time, performing without excessive structural deformations (deflection and/or strain) (Cobb Fiona, 2004, p55).

4.1 Comparison between the growing tree and tree-like structures

As mentioned before (section 1.2), natural trees are subjected to compression and tension forces. The following example demonstrates the influence of these stresses in a simulated tree and constrained tree-like structure (bound to a grid). Both examples resemble the tree-like structural typology of Stuttgart Airport.

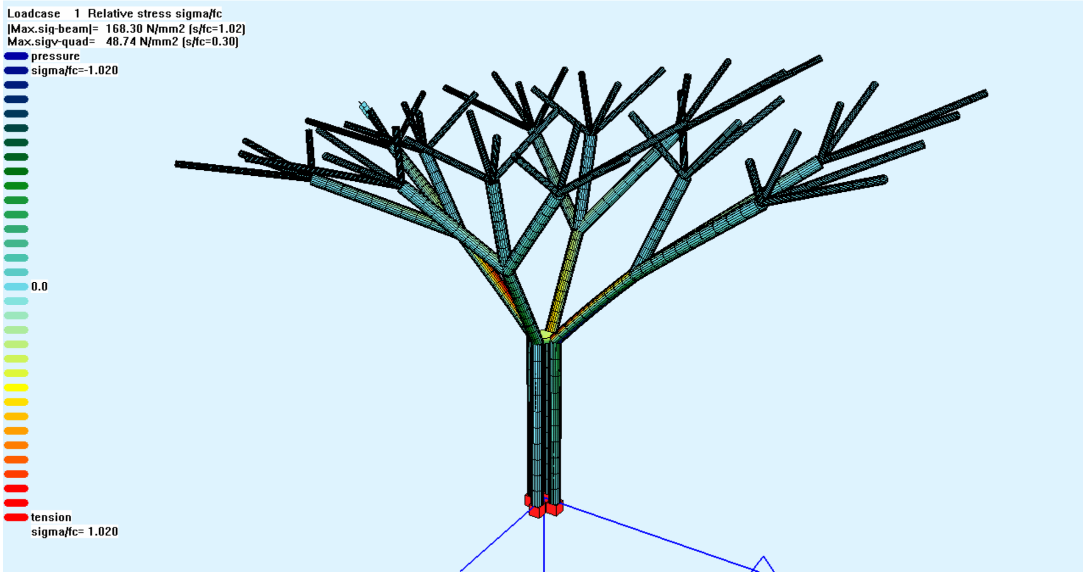


Fig 4.1 Stuttgart Airport branching tree-like system without the grid on top.

The branches of the natural tree are connected on only one side, while the other end of the branch stands free, having more room for expansion under applied external forces (wind, earthquakes, snow, dead loads). In buildings, this has to be controlled to avoid structural deflection. Fig. 4.2 illustrates how this deformation can be controlled by bounding the free branches to a corona (horizontal grid).

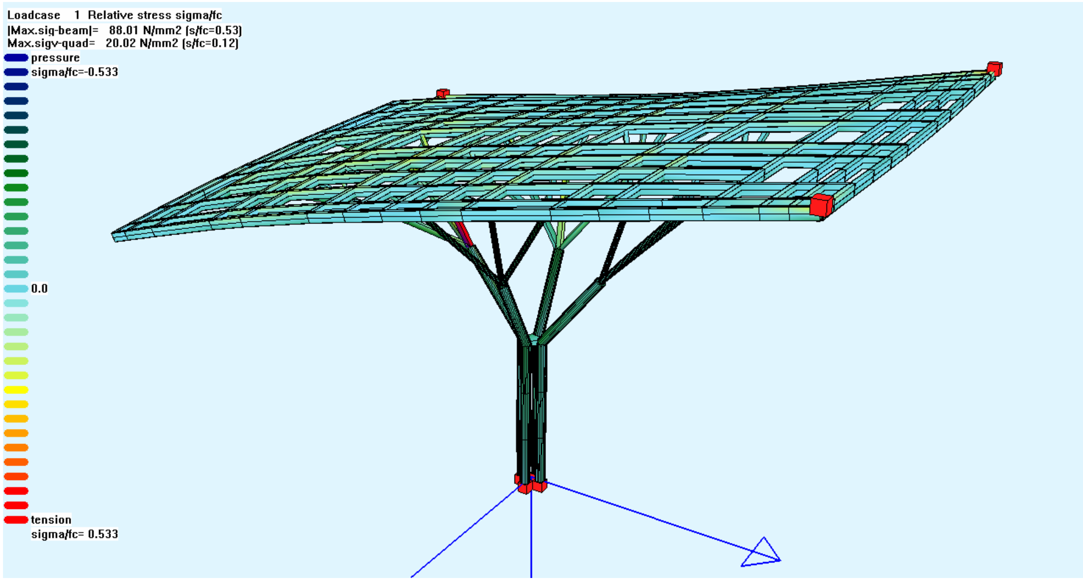


Fig 4.2 Stuttgart Airport tree-like system with the grid - steel material.

The •/*fc* reduction factors for steel and wood by using a bound grid are quantified in table 4-1.

Table 4.1 •/*fc* values for steel and wood

	Steel	Wood
Free tree	1.020	1.715
With grid	0.533	0.916

The deflection of the natural tree is 0.423 meters. Simulation results show that this value is reduced 60% by the applying a grid on top of the tree.

4.2 Morphological Comparison of the Base Cases

The influence of geometric criteria, e.g., complexity, proportional dimensions, symmetry, multiple branching system (bifurcated, trifurcated etc) will be assessed in chapters 4.5 through 4.10. For each base case, several materials are going to be compared as well as the geometry (cross sections).

The Beaverton library tree-like column structure will be compared with the Stuttgart Airport structure. The glue-laminated wood will be replaced with a tubular steel structure. The diameter of the tubular elements will change according to the natural law of scale. The Beaverton Library structural system is smaller compared to Stuttgart Airport. The Beaverton branches form a square configuration, whereas Stuttgart branches are distributed to support the rectangular grid. Therme Bad Oeynhausen has curved shape and the comparison of such shape with the previous ones (rectangular) would not have any physical meaning.

4.3 Natural Law of Scale

The bigger the structure becomes the thicker in relation to its length. As thickness increases the beam is subject to bending loads. The increase of the dead load is greater to the power of three (3) in volumes, compared to the load bearing capability that is increased by the power of two (2). In case a 10- meter span requires a beam of 0.20 meters thickness, 10x10 times, a beam of 20 meters thickness with the whole weight increasing by a factor of 1000. Therefore, neither design nor the nature allows us to design something enormously large as span structure. There are some limits determined by the natural laws of what is considered constructible and what is not (Schleich, J. and Bergermann, R., 2004, p 309). Just as nature does not permit the overgrowth of the trees; otherwise their branches could brake due to their own dead load.

In order to avoid the increase of the volume by the power of three, for the purpose of simulation we are going to reduce the structure to match particular structure with something smaller and logically comparable. The reduction of the columns is not going to be rooted, but rather the same percentage of reduction for the whole structure. In this sense, the column will be slightly thicker in the reduced version.

Stuttgart Airport structure will be compared with the Beaverton Library. The length of the grid is twice as long as the width 2a = b. To compare with Beaverton Library structure, the split of this rectangular into two identical squares must be taken into consideration.

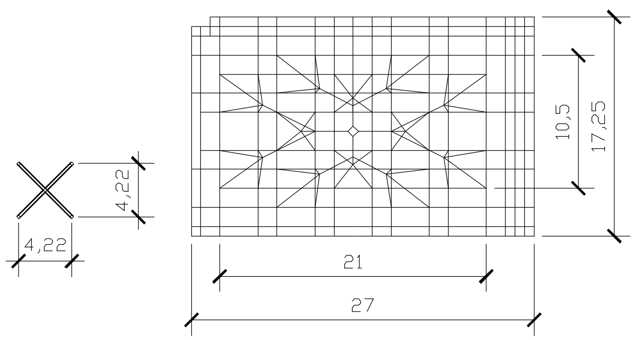


Fig 4.3 Proportional dimensions of tree-like structures for Beaverton Library and Stuttgart Airport

A reduction of 48.69% of the structure creates perfect conditions for comparing the materials against the morphological model.

The sets of cross sections (rectangular or circular) vary due to the natural law of scale. Therefore the reduction factor applies to both cross sections and to the morphology of the structure. The reduction factor will result in smaller tubular steel or any other rectangular steel elements.

<u>Base sets of Parameters</u>

The Beaverton columns are the reference dimensions for comparing these three base cases.

The surface of the Stuttgart Airport tree column will be reduced to the surface of Beaverton Library. The cross sections are reduced too. The height reduction percentage was taken into consideration.

4.4 *Stuttgart Reduced*

After the reduction the new cross sections for the Stuttgart Airport are:

- § Main tubular columns: • – 203 mm
- § Tree branches: • – 101.5 mm
- § Roof grid support: h/b – 105 mm

The thickness of the tubular steel elements remains unchanged.

This reduction is done in accordance with the natural law of scale by comparing tree-like structures of different dimensions.

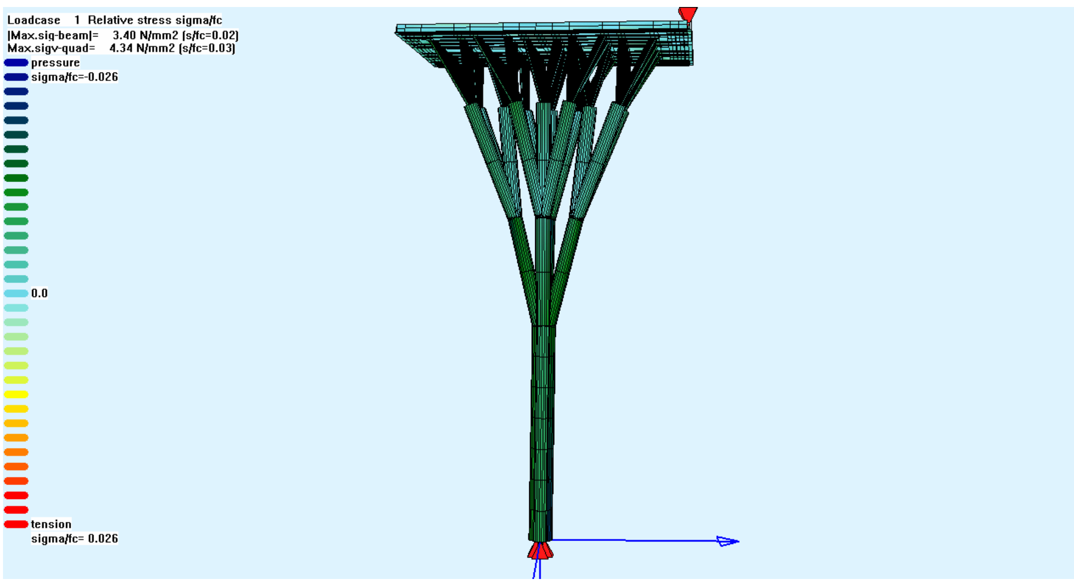


Fig 4.4 Stuttgart Airport reduced.

As we can see from the picture, such a prototype of branching distribution is illogical. The idea behind tree-columns is to distribute the roof loads in compression with little bending forces. Crowding these branches makes no sense, and eventually we are misled in our assumptions. The amount of branches is unnecessary, because the branches have to load bear a smaller surface (the grid is reduced, accordingly, too and therefore needs to be simplified). The following example, fig.4.5, shows the reduction of the above branches into four similar fundamental branches, which evolve into additional four small sub-branches.

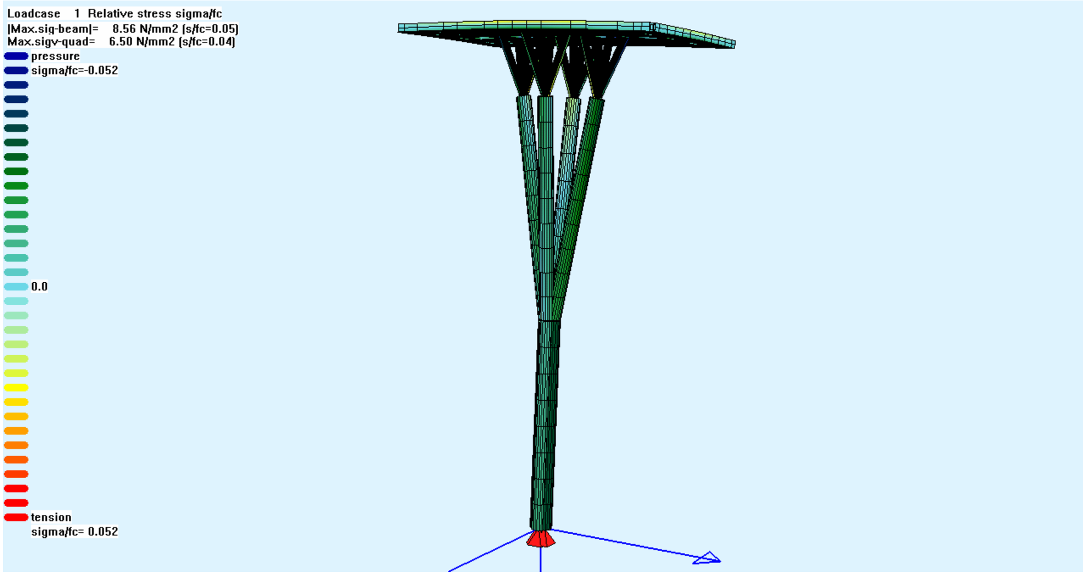


Fig 4.5 Reduction of branches for “Stuttgart Airport reduced”.

As shown in the fig. 4.5, the system requires only four branches to bear the grid load system.

4.5 Beaverton Library – cross sections derived from Stuttgart Airport

The challenge is to model the Beaverton Library structure using the above mentioned sets of parameters that derive from Stuttgart Airport.

New Beaverton Library cross sections:

§	Main tubular columns:	• – 203 mm
§	Tree branches:	• – 101.5 mm
§	Roof grid support:	h/b - 105 mm

All these parameters will be replaced with Stuttgart Airport cross sections and reduced 48,69% based on the natural law of scale. This reduction is necessary to carry out comparative analysis based on the original dimension of the library.

4.5.1 **Steel**

It is illogical to proceed with the steel materials having the same morphology and shapes as with the glulam wooden structure. Therefore tubular cross sections were introduced. These cross sections will be used throughout all the hybrids of Stuttgart and Beaverton Library simulations. The tubular system will consist of four branches (with no further sub-branches).

Table 4.2 Cross sections

Cross section/Material	Width (cm)	Length (cm)
Main trunk/Tubular steel	20.3 diameter	
Branches/tubular steel	20.3diameter	
Roof grid/steel	10.5	10.5

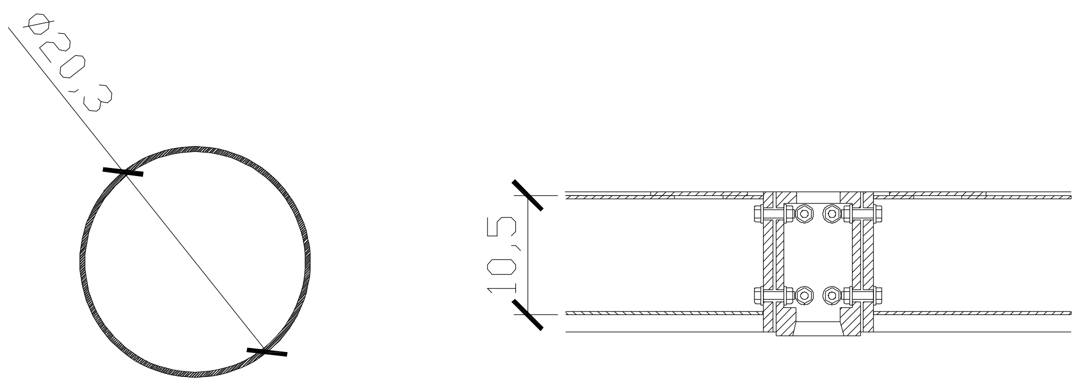


Fig 4.6 Reduced cross sections.

4.6 Case 1: Stuttgart Airport – Wood material.

For the purpose of comparison, steel material is going to be replaced with wood, with equivalent cross sections (except that wood is massive and steel is hollow), to assess the material performance in the structure. Comparison analysis is carried out using BUILD software where equivalent load cases are applied.

Table 4.3 Wooden cross sections for Stuttgart Airport.

Building element	Profiles	Diameter (mm)	Height (mm)	Width (mm)
Main trunk	cylindrical shape	406.4		
Branches	cylindrical shape	203.2 and159		
Roof grid	rafters		340	150

Table 4.4 Simulation results, Stuttgart Airport, wood material

Wood								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	1.847	18.47	0.316					
LC2					15.771			
LC3	0.042	0.42	0.009	1.173				
LC4	0.035	0.35	0.007	0.871				
LC5	0.087	0.87	0.013	0.733				
MODEL PARAMETERS						64.835	800	51868

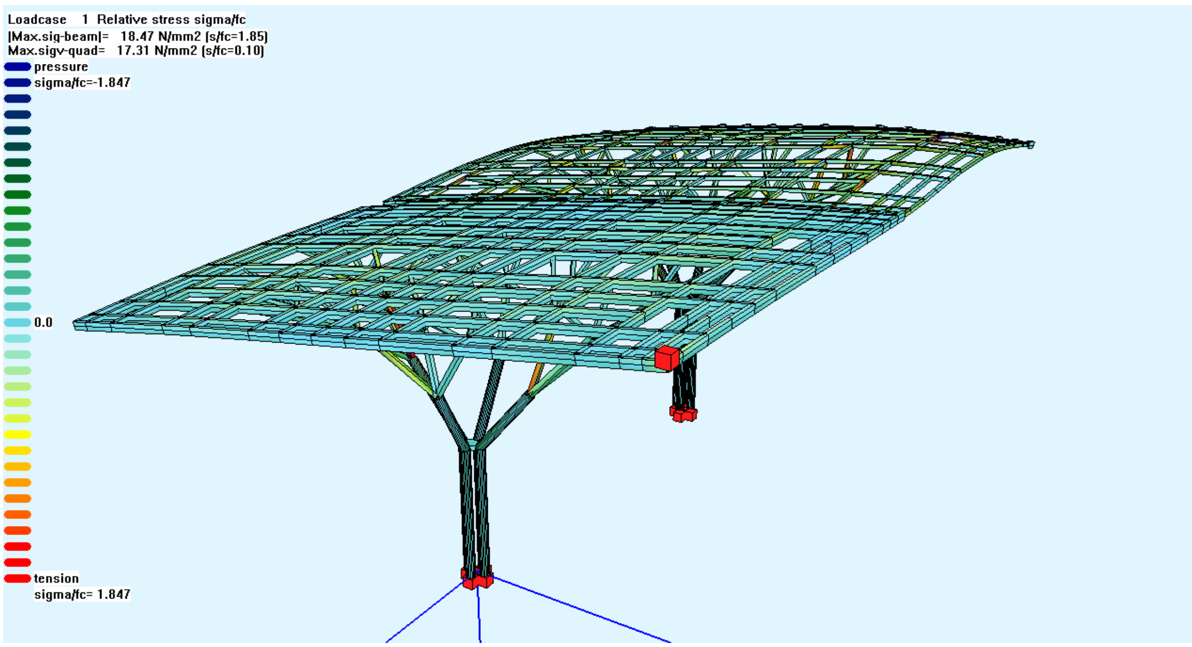


Fig 4.7 Visualization of the stresses applied to the Stuttgart Airport structure under the sole influence of the dead load, wood material.

Fig. 4.7 shows that this system is not stable because the load induced in the structure is 84.7% above the admissable strees for the material (wood). This result indicates that wooden material is not appropriate for this type of morphology, since the deformations/deflection expected can be as big as 0.316 meters, which eventually would result in the collapse of the structure.

The following screenshot, fig 4.8 is relevant to the stability factor, load case 2. The stability factor based for the same morphology and cross sections is smaller in wood (15 times its own dead load, table 4.4) than in steel structure (43.88 times its own dead load, table 3.2).

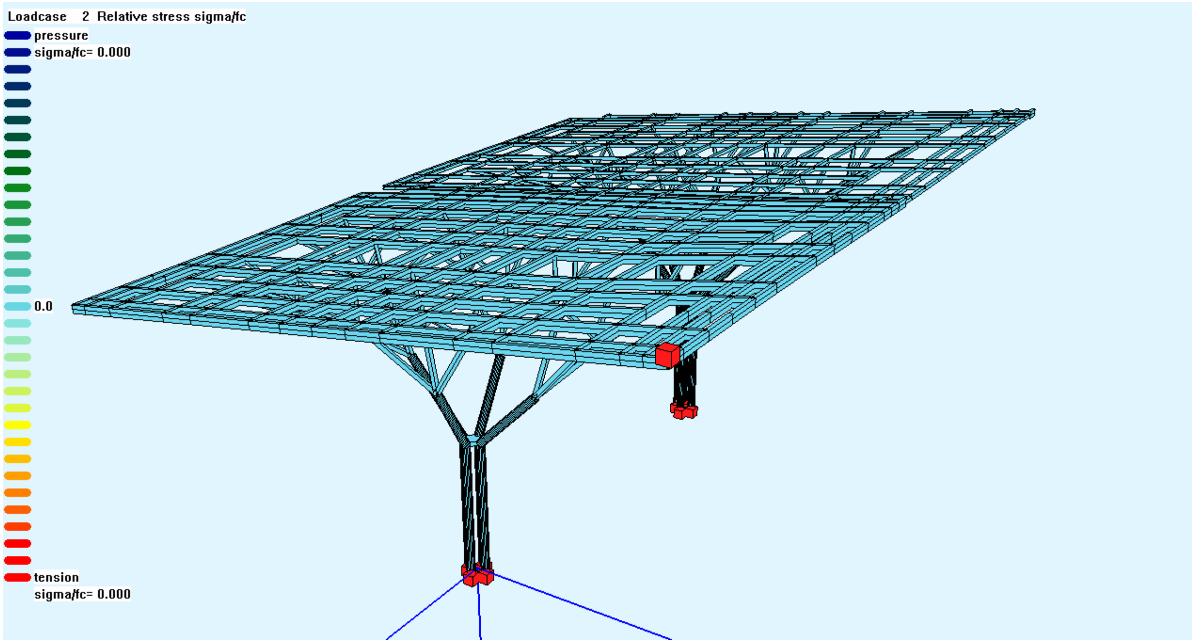


Fig 4.8 Visualization of the stability factor (load case 2), Stuttgart Airport, wood material.

The following three screenshots (fig 4.9, 4.10 and 4.11) illustrate the load cases 3 to 5 resulting deflections and stresses of the construction due to standardized earthquake based on predefined magnitudes in BUILD program database. Figs 4.8, 4.9, and 4.10 indicate different relative stress results for wood (compare table 3.2 with 4.4). The comparison between steels and wood structure is presented in the graphs 4.1- 4.6.

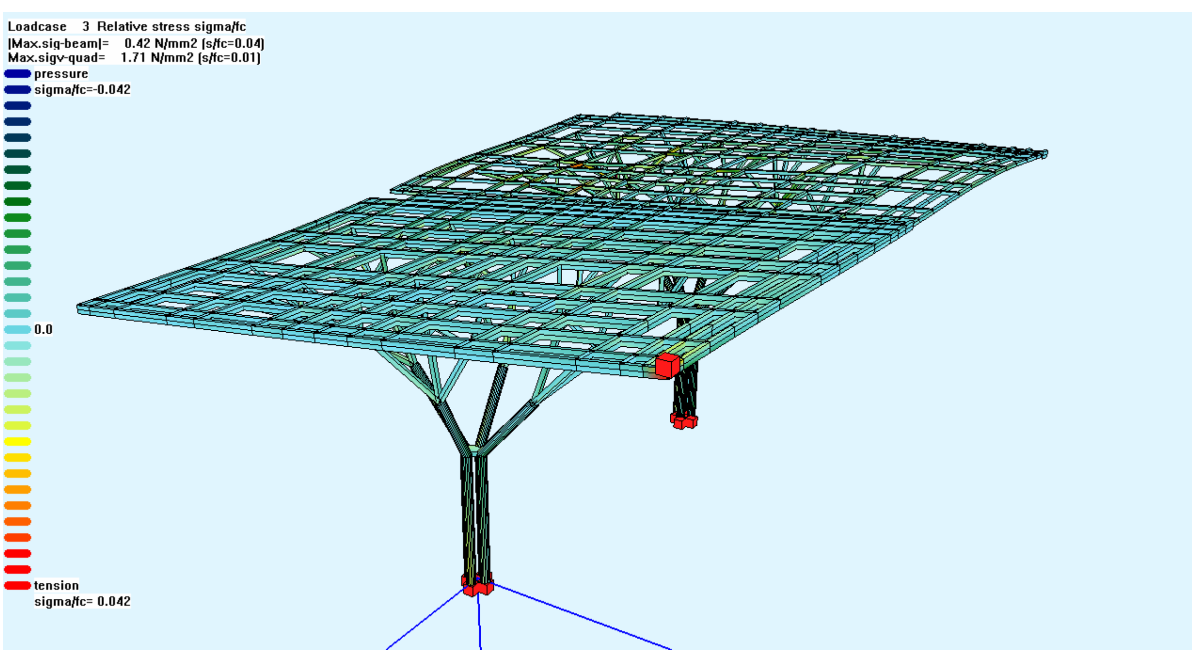


Fig 4.9 Visualization of the stresses induced by load case 3, Stuttgart Airport, wood material.

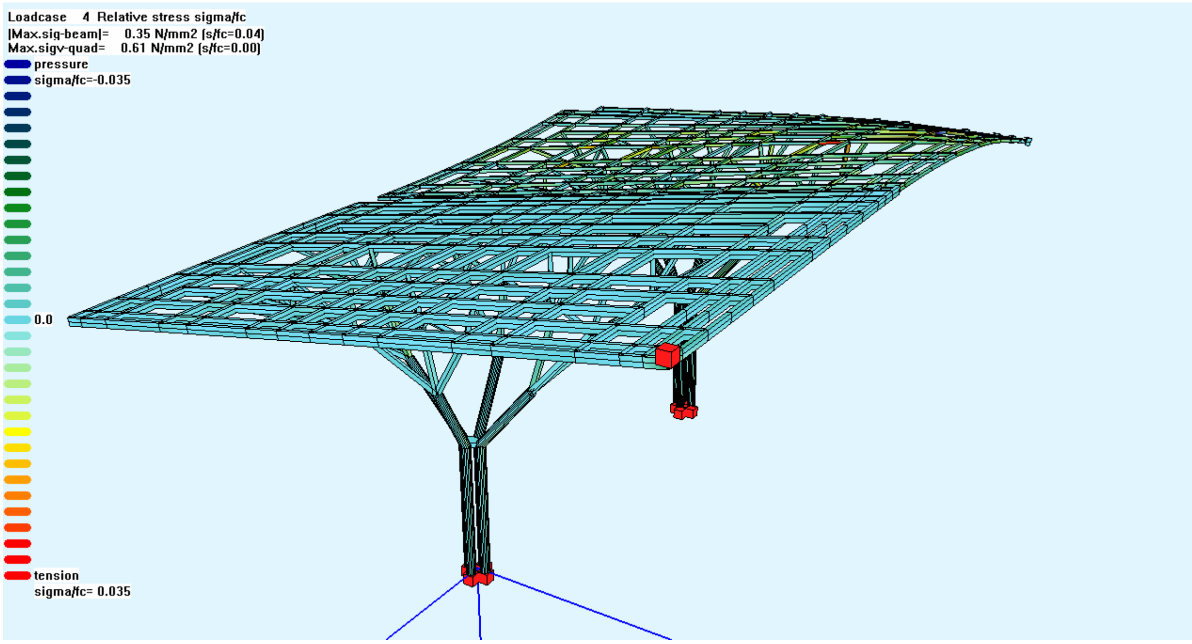


Fig 4.10 Visualization of the stresses induced by load case 4, Stuttgart Airport, wood material.

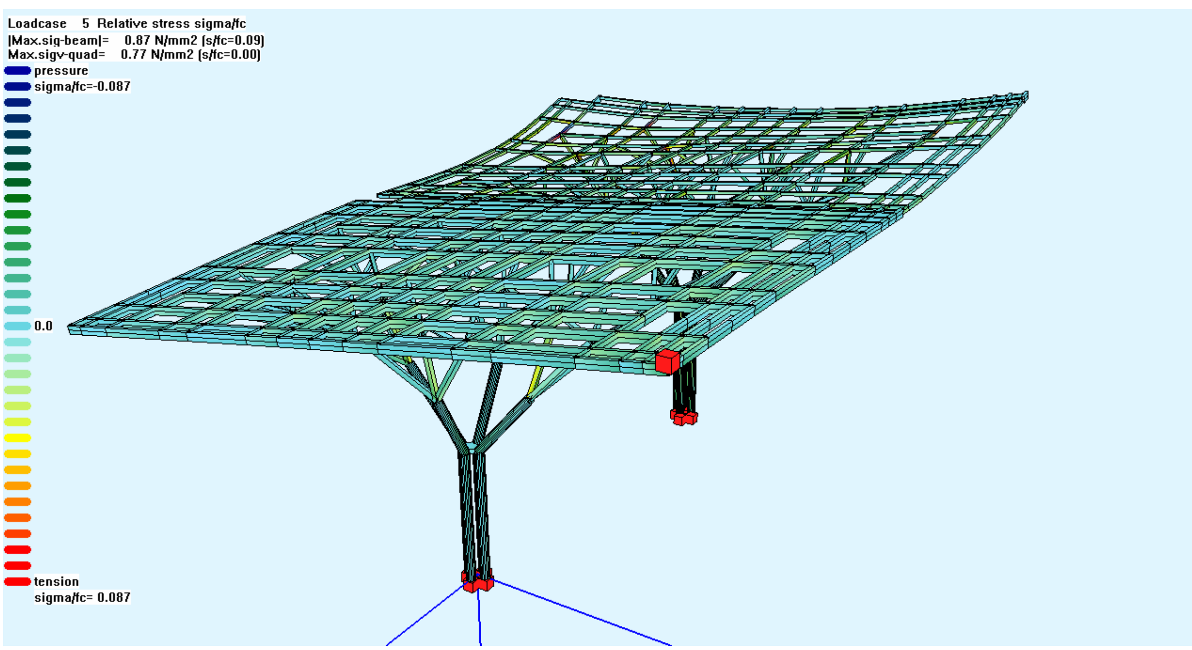
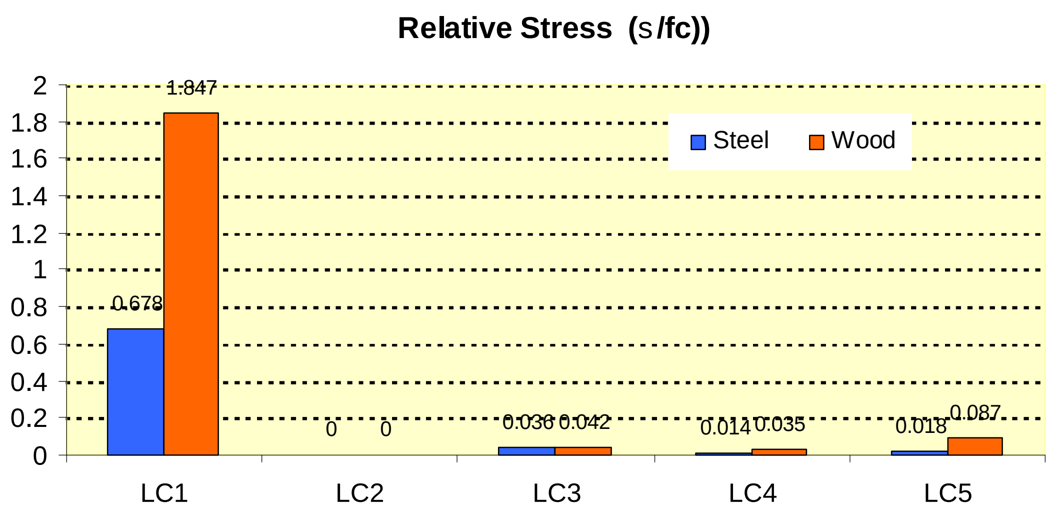


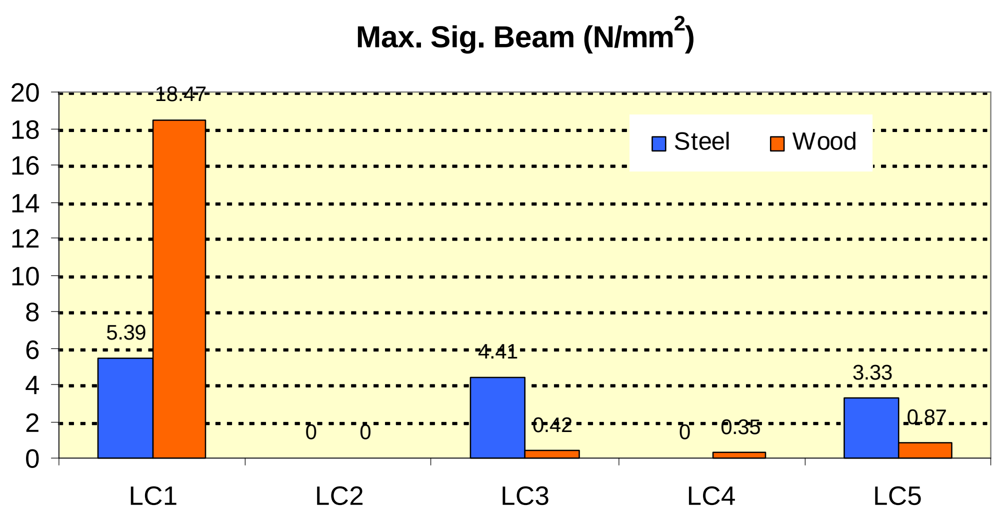
Fig 4.11 Visualization of the stresses induced by load case 5, Stuttgart Airport., wood material.

The following graph 4.1 illustrates the relative stress difference between the same type of morphology but for two different materials (wood and steel). Load case 1 for wood materials shows that the relative stress is 85% above the admissible stress for the material. This structure and material will enter the plastic range and the expected deformations are immense and irreversible.

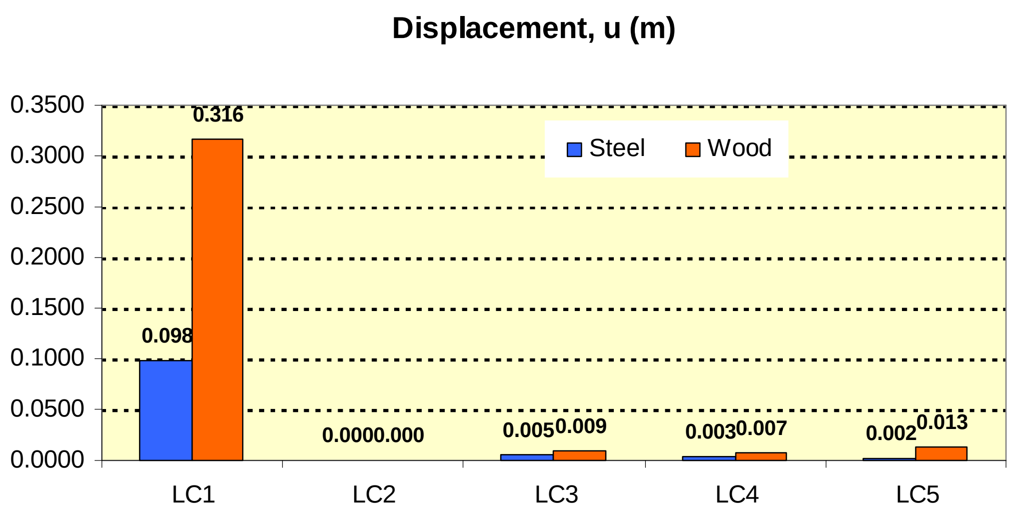


Graph 4.1 Relative stress comparative analysis for Stuttgart Airport structure in steel and wood.

The following graph 4.2 represents the maximum load that can be supported by the structure per unit of area. It is a comparative simulation for wood and steel materials in Stuttgart Airport.



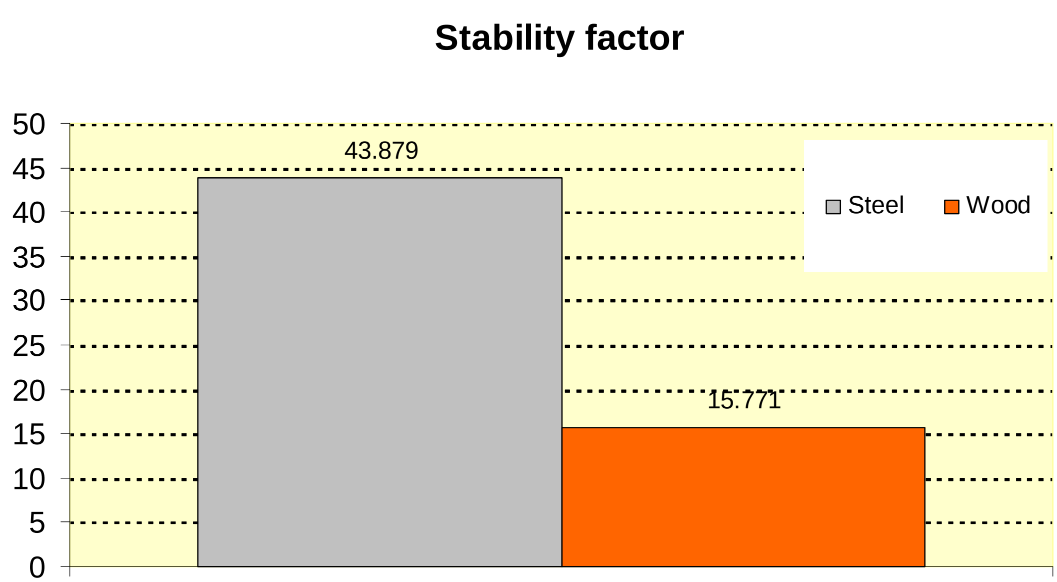
Graph 4.2 Maximum sigma comparative analysis for Stuttgart Airport structure in steel and wood.



Graph 4.3 Deformation comparative analysis for Stuttgart Airport structure in steel and wood.

The graph 4.3 is a presentation of different displacements applied to the same type of morphology. The overall deformations on wooden materials are greater in all load cases than in steel. The load case 1 shows that the overall difference on displacements on steel is 10 cm whereas on wood 31.6 cm.

The following graphs illustrate that the stability factor for steel is almost three times higher than for wood.



Graph 4.4 Stability factor comparative analysis for Stuttgart Airport structure in steel and wood.

4.7 *Case 2: Hybrid Beaverton-Stuttgart*

The structural behaviour of the hybrid Beaverton-Stuttgart, subjected to the parameters above, was simulated for several load cases. The hybrid Beaverton-Stuttgart will be simulated only with steel because wood proved to be structural unstable for this particular morphology. The first comparison is performed between the Beaverton Library structure (wood-table 3.3) and the hybrid Beaverton-Stuttgart (steel- table 4.5).

Table 4.5 Structural simulation results for hybrid Beaverton-Stuttgart, reduced version

Steel									
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Vibration Time (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.033	5.39	0.000					
LC2					549.97			
LC3	0.027	4.41	0.002	0.335				
LC4	0	0	0	0.272				
LC5	0.02	3.33	0.01	0.264				
MODEL PARAMETERS						1.297	7850	10181.45

The following figures show the BUILD program animation of structural behaviour of hybrid Beaverton-Stuttgart. The fig 4.12 is another screenshot from BUILD program to visualize the relative stress applied to hybrid between Beaverton and Stuttgart.

The structural grid is subjected to considerable tension (red colour). The relative stress is very low, only 0.033 whereas displacements are 0 meters. Based on these results we can conclude that the relative stresses induced in steel and wood are of the same order of the magnitude. The comparison of two results is presented in graph 4.5. However, the load bearing capability of steel is higher 12.8 times than wood (graph 4.6).

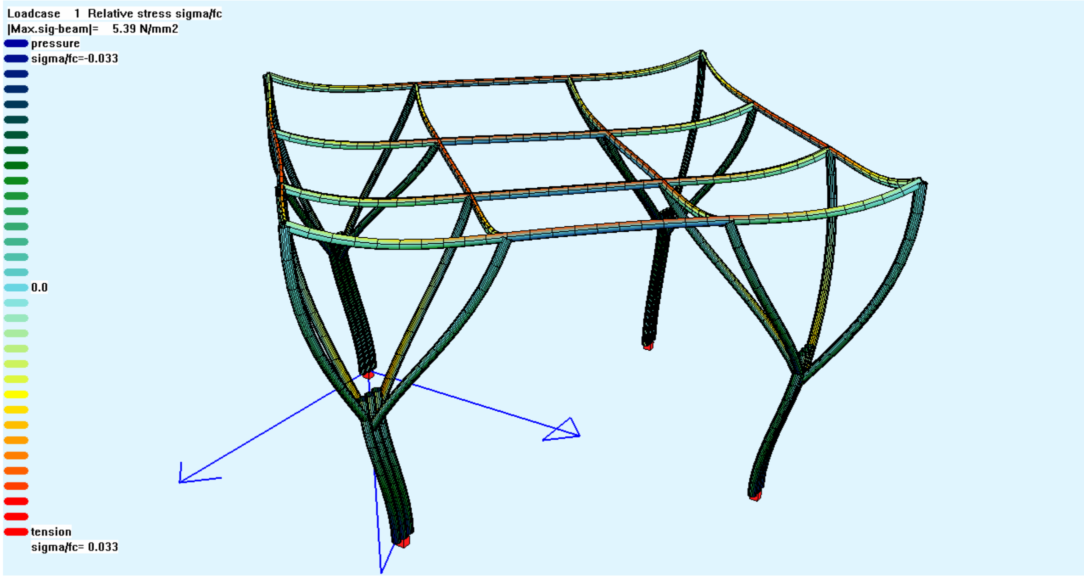


Fig 4.12 Visualization of the stresses applied to the hybrid Beaverton-Stuttgart, under the sole influence of the dead load.

Fig 4.13 illustrates the result of the structural form due to the application of the stability factor (load case 2) for hybrid between Beaverton and Stuttgart structure. This structure can support its own dead load 550 times, or a total of 35,497.92 kg per square meter.

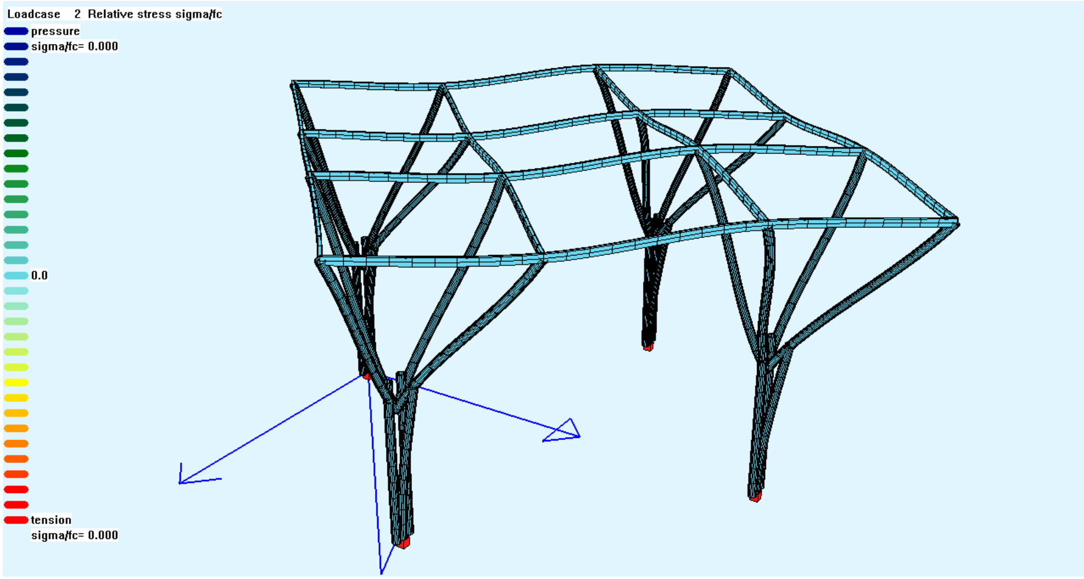


Fig 4.13 Visualization of the stability factor (L2), hybrid of Beaverton-Stuttgart

Fig 4.14 represents the simulation of load case 3 as a result of standardized earthquakes. The relative stress subject to the earthquake for this load case is relatively low, 0.027, and the displacement is only 0.002 m.

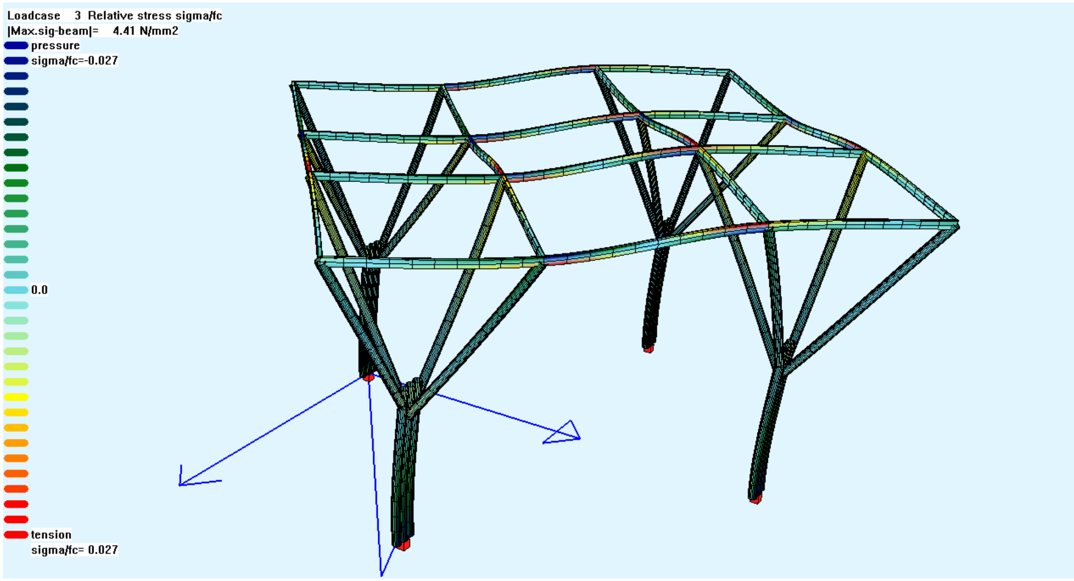


Fig 4.14 Visualization of the stresses induced by load case 3 (L3), hybrid of Beaverton-Stuttgart

In the following illustrated case fig 4.15, the earthquake has no effect on the structure. The BUILD program shows no deformations for this load case.

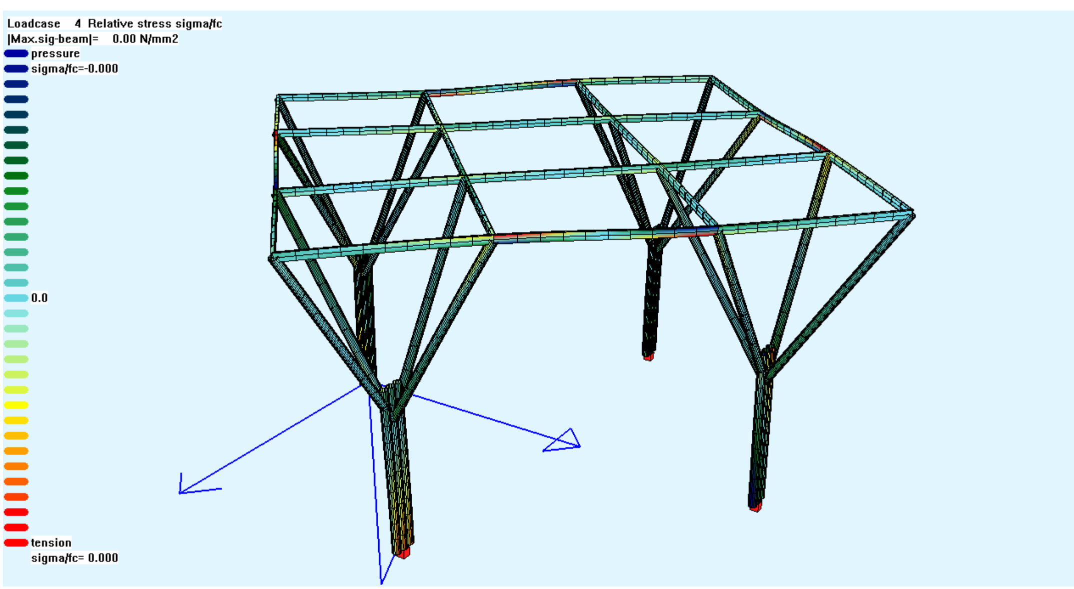


Fig 4.15 Visualization of the stresses induced by load case 4 (L4), hybrid of Beaverton-Stuttgart

The screenshot, fig 4.16 shows different deformations due to different vibration directions. The simulation shows that the displacement, 0.001 meters, has tendency to vibrate in the opozite horizontal direction with the previous load case 3. The relative stress given from the load case 5, 0.02 is exceptionally low and the structure is exceptionally resistant to the earthquakes.

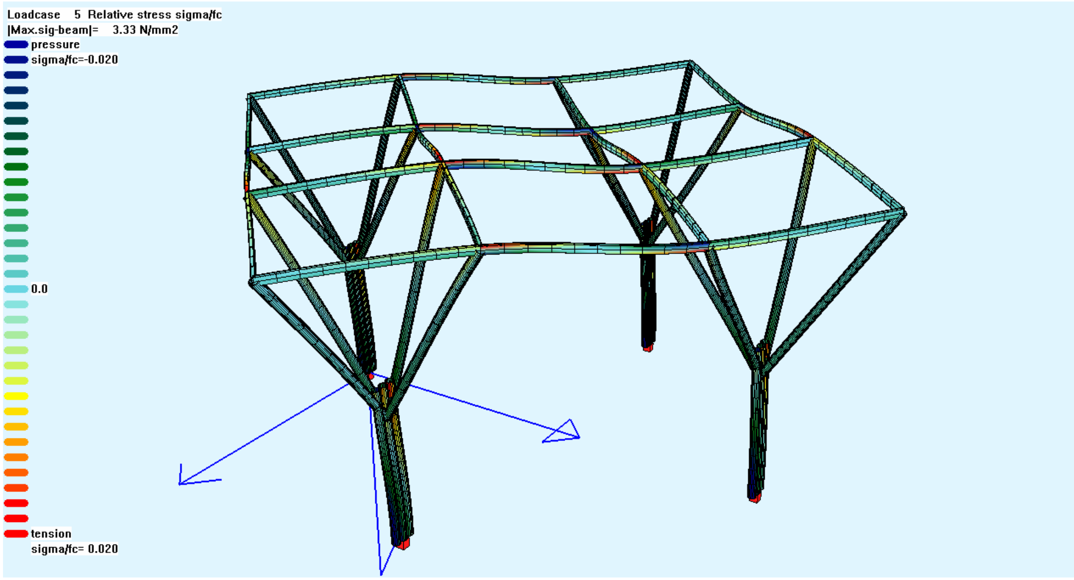
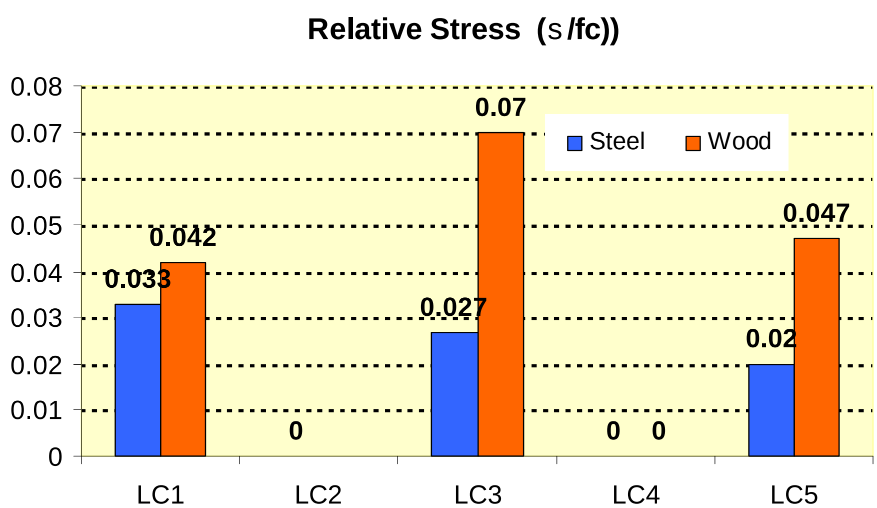
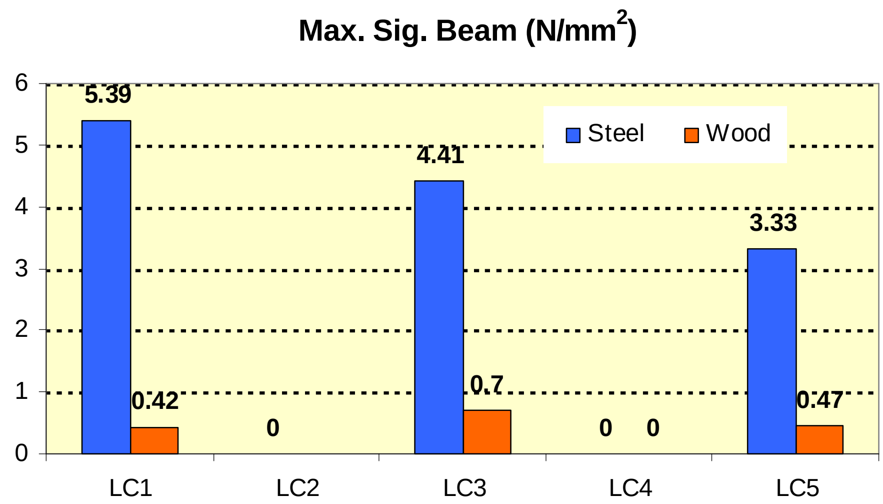


Fig 4.16 Visualization of the stresses induced by load case 5 (L5), hybrid of Beaverton-Stuttgart



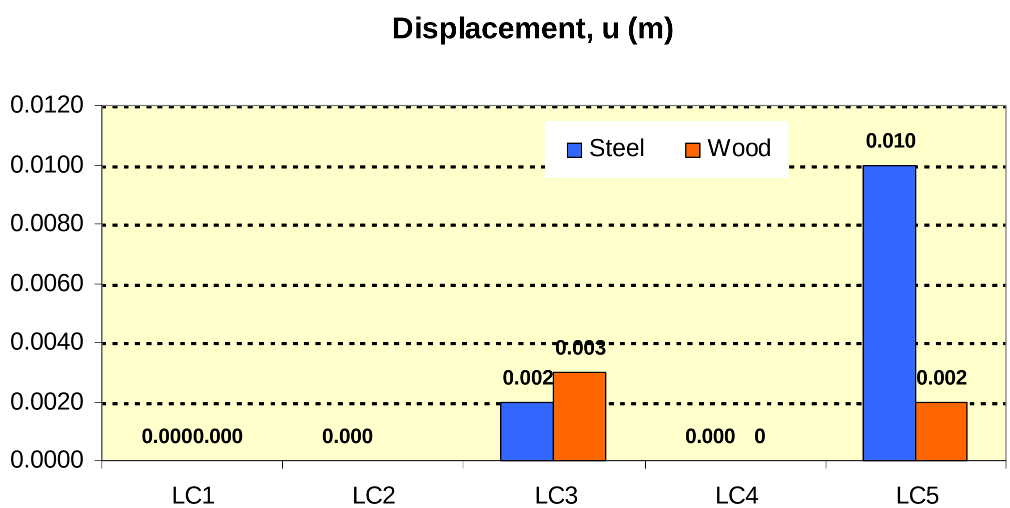
Graph 4.5 Comparison of relative stresses between Beaverton Library and hybrid Beaverton Stuttgart for different materials (wood and steel).

Graph 4.7 indicates that the relative stress is reduced by a factor of 30%, 60%, and 35%, for LC1, LC3 and LC5, respectively, when using steel material. This shows that in case of earthquakes (LC3 and LC5), the steel structure based on Stuttgart airport tubular steel profiles (the hybrid between Beaverton and Stuttgart) would have slightly better performance. The next graph confirms this conclusion: steel has 12.8 times higher load bearing capability for LC1.



Graph 4.6 Comparison of the maximum sigma between Beaverton Library and hybrid Beaverton Stuttgart for different materials (wood and steel).

The graph 4.8 shows that steel has greater resistance to heavier loads than wood. When using steel, the maximum sigma beam increases by a factor of 12.8, 6.3, and 7.08, for LC1, LC3, and LC5 respectively.



Graph 4.7 Comparison of the deformation between Beaverton Library and hybrid Beaverton Stuttgart for different materials (wood and steel).

The previous graph indicates that, wood is subjected to smaller displacements with increasing the load cases..

4.8 Case 3: The Hybrid of Stuttgart-Beaverton (increased morphology dimensions).

The following case study will examine the structural behavior of the same structure and morphology in enlarged version. This enlargement will be identical to the existing dimensions of Stuttgart Airport structure. In this case study we will examine the structural performance of both tubular steel and glulam structure.

Table 4.6 Cross Section: Tubular Steel Increased

Cross section/Material	Unit	Width	Length
Main trunk/Tubular steel	mm	406.4 diameter	
Branches/tubular steel	Mm	203.2 diameter	
Roof grid/steel	Mm	200	200

Table 4.7 Structural simulation results for Stuttgart-Beaverton, increased version

Steel								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.067	11.06	0.001					
LC2					270.383			
LC3	0.04	6.65	0.005	0.609				
LC4	0.034	5.56	0.004	0.53				
LC5	0	0	0	0.504				
MODEL PARAMETERS						2.19	7850	17191.5

The following figures show the BUILD program animation of the structural behaviour of tubular steel for the hybrid Beaverton-Stuttgart enlarged version. The fig 4.16 refers to relative stress for load case 1, which is all over again low, 0.067, and an insignificant displacement of 1mm.

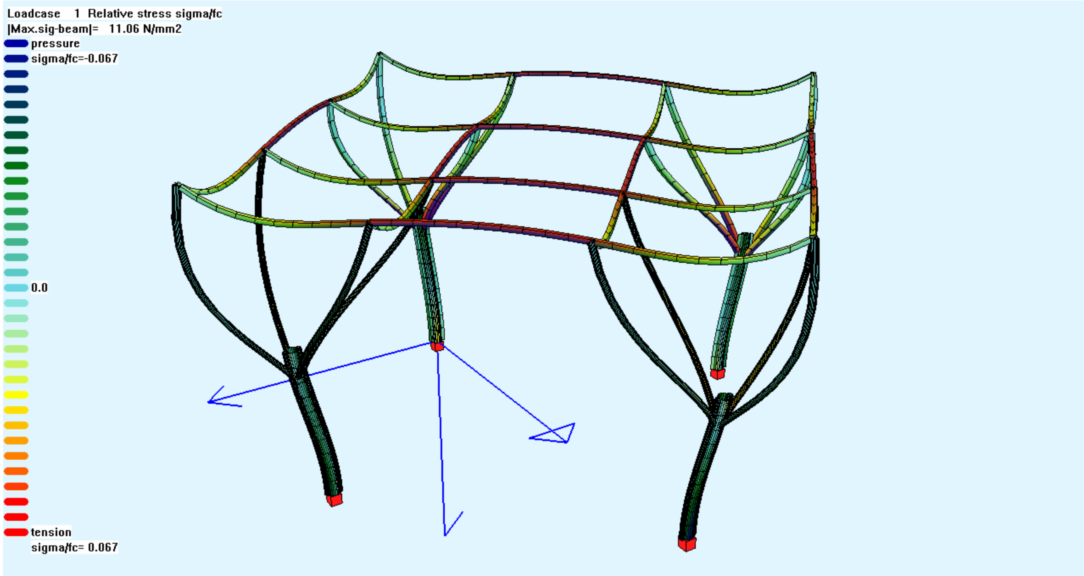


Fig 4.17 Visualization of the stresses applied to the hybrid Beaverton-Stuttgart, under the sole influence of the dead load – enlarged version.

Fig 4.18 illustrates structural form resulting from the application of the equivalent to a stability factor. (load case 2) for the hybrid between Beaverton and Stuttgart enlarged version. This structure can support its own dead load 270.383 times, or a total of 4,648,289.35 kg, or 35,497.92 kg per square meter which is twice as less as for the initial hybrid of Stuttgart - Beaverton. This simulation result is also the evidence that nature does not permit us to design something large beyond ordinary design imagination. The stability factor would eventually not comply with our imagination.

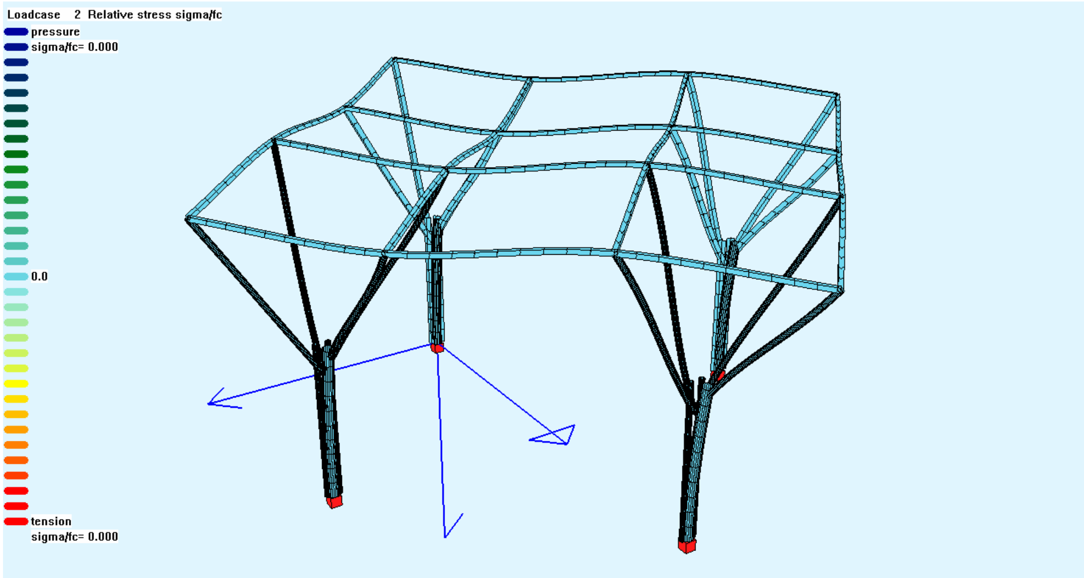


Fig 4.18 Visualization of the stability factor (L2), hybrid of Beaverton-Stuttgart - enlarged version.

Fig 4.19 represents the simulation of load cases 3 as a result of standardized earthquakes. The relative stress produced by the earthquake for this load case is again relatively low, 0.040, and the displacement is only 0.005 m.

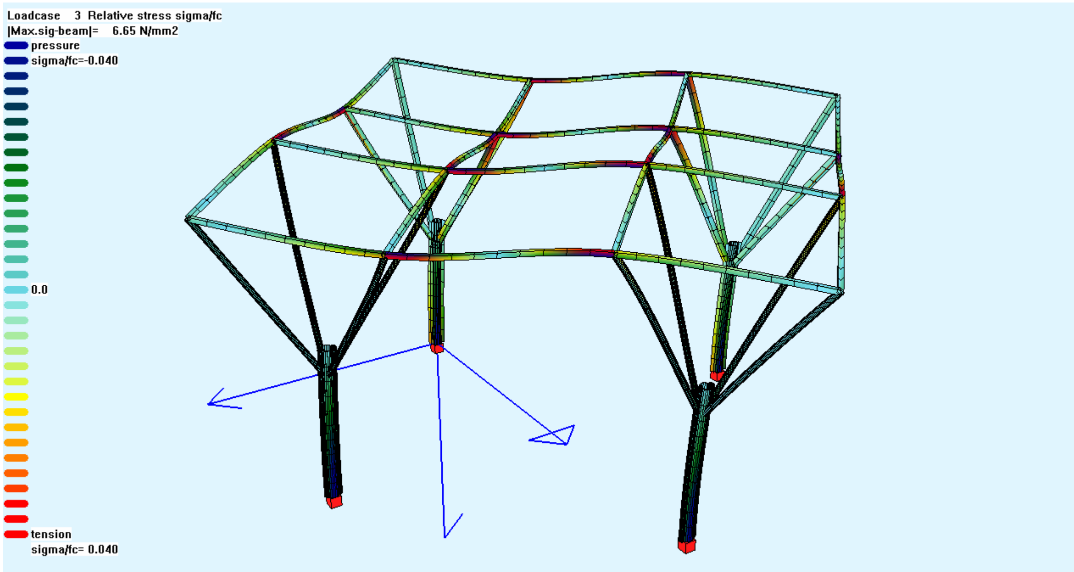


Fig 4.19 Visualization of the stresses induced by load case 3 (L3), hybrid of Beaverton-Stuttgart - enlarged version.

Fig 4.20 represents the simulation of load cases 4 as a result of standardized earthquakes. The relative stress subject to the earthquake for this load case is relatively low, 0.034, and the displacement is small 0.004 m.

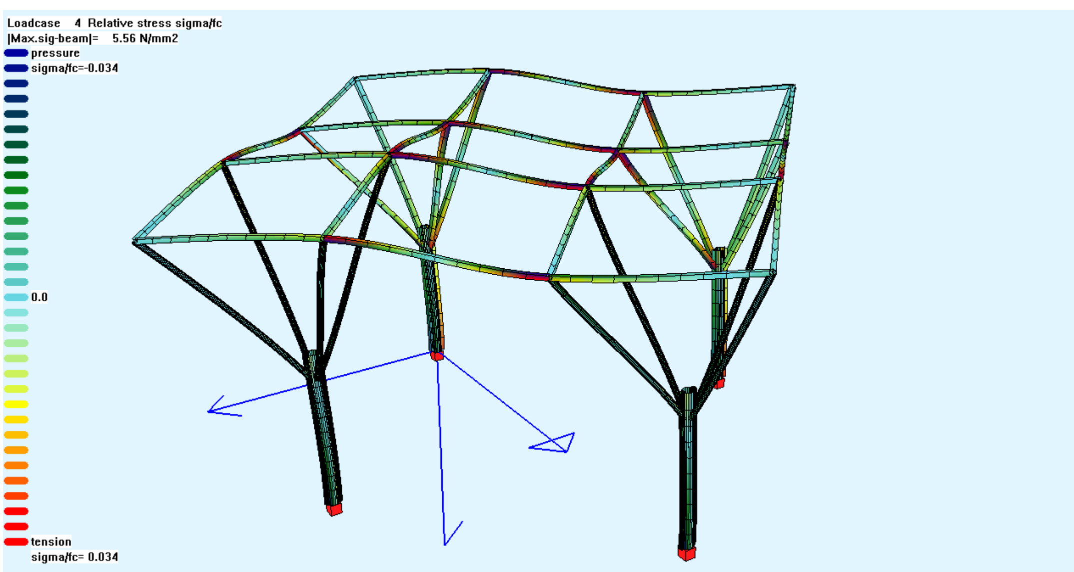


Fig 4.20 Visualization of the stresses induced by load case 4 (L4), hybrid of Beaverton-Stuttgart enlarged version.

Fig 4.21 represents the simulation of load case 5 as a result of standardized earthquakes. However, the BUILD program shows that the earthquake has no effect on the structure.

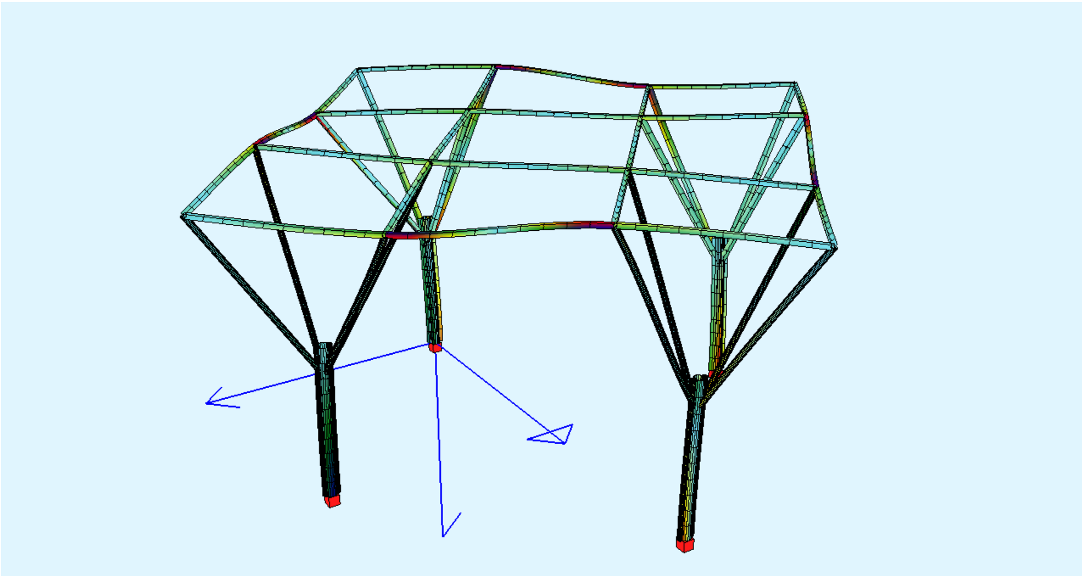


Fig 4.21 Visualization of the stresses induced by load case 5 (L5), hybrid of Beaverton-Stuttgart - enlarged version.

The following table represents the results of the simulation for the hybrid Stuttgart-Beaverton using wood.

Table 4.8 Structural simulation results for Stuttgart-Beaverton, increased version for wood material

Wood								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm²)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m³)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.061	0.61	0.001					
LC2					186.073			
LC3	0.09	0.98	0.006	0.651				
LC4	0	0	0	0.53				
LC5	0.071	0.71	0.003	0.47				
MODEL PARAMETERS						89.43	800	71544

The fig 4.22 is a screenshot from BUILD program to visualize the relative stress applied to glulam enlarged for the hybrid Beaverton and Stuttgart.

Here we can also observe that structural wooden grid is subjected to considerable tension (red colour). The relative stress is very low, only 0.061, whereas displacements are 0.001 meters.

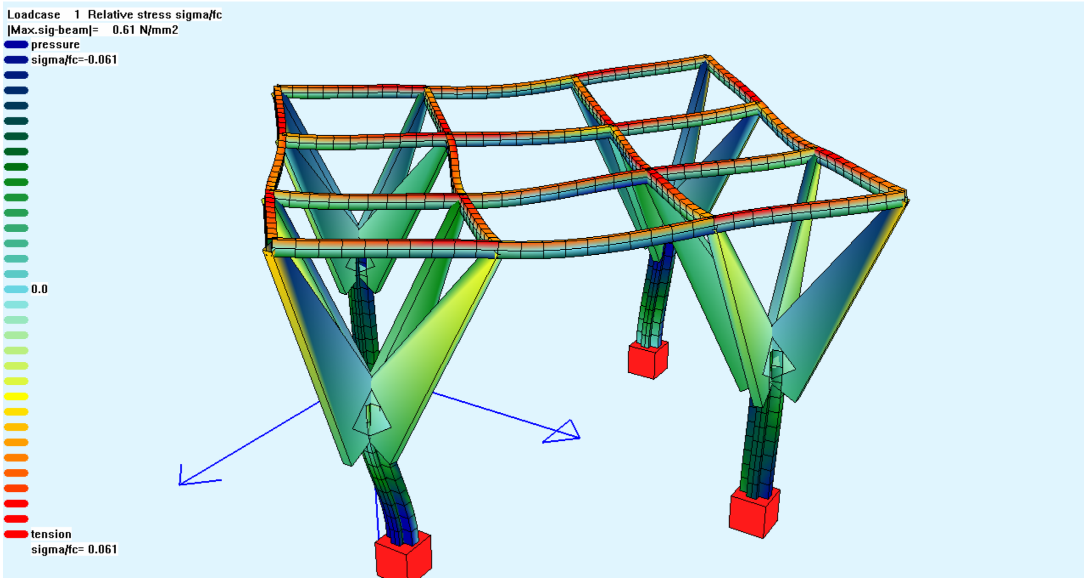


Fig 4.22 Visualization of the stresses applied to the Beaverton Library structure under the sole influence of the dead load – enlarged version.

The following screenshot, fig 4.23 is relevant to the stability factor, load case 2. The stability factor is 186.073 times higher than its own dead load, 13,312,406.71, or 84387.34 kg per square meter.

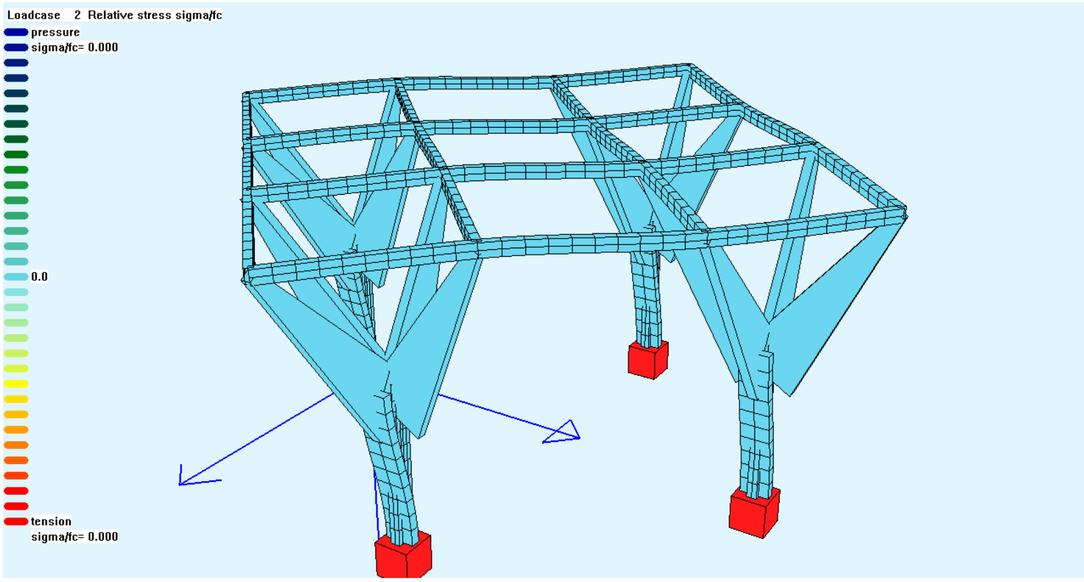


Fig 4.23 Visualization of the stability factor (load case 2), Beaverton Library – enlarged version.

Fig 4.24 shows the stress induced by a standard earthquake corresponding to load case 3. The BUILD program shows that the relative stress is 0.09. The displacement is 0.006 meters.

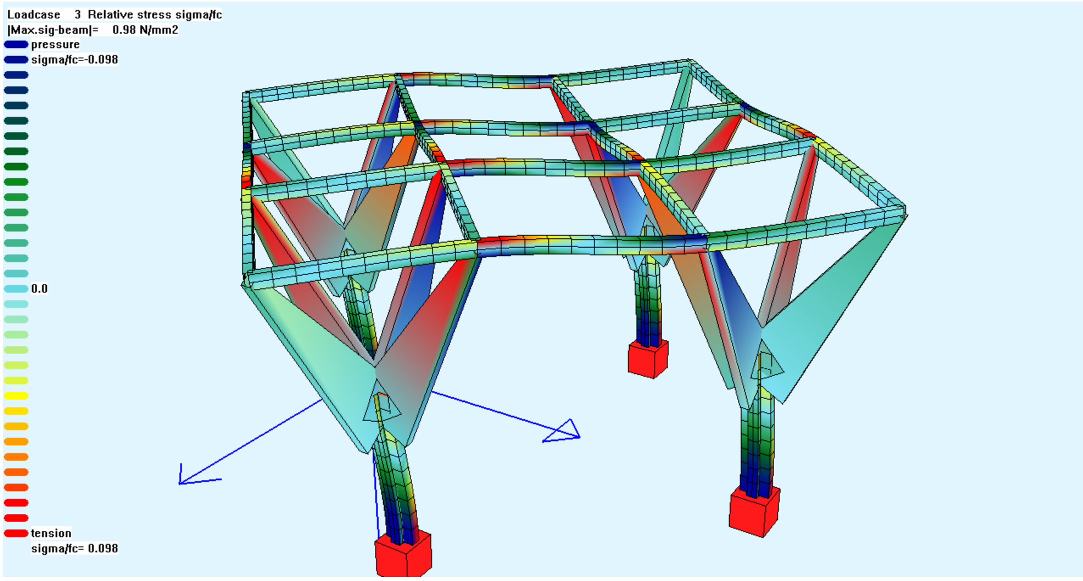


Fig 4.24 Visualization of the stresses induced by load case 3, Beaverton Library – enlarged version.

Data from the simulation visualized in fig. 4.25 shows that the effect of an earthquake on the structure can be neglected, whereas in load cases (fig. 4.26), the earthquake causes structural displacement of 3 mm.

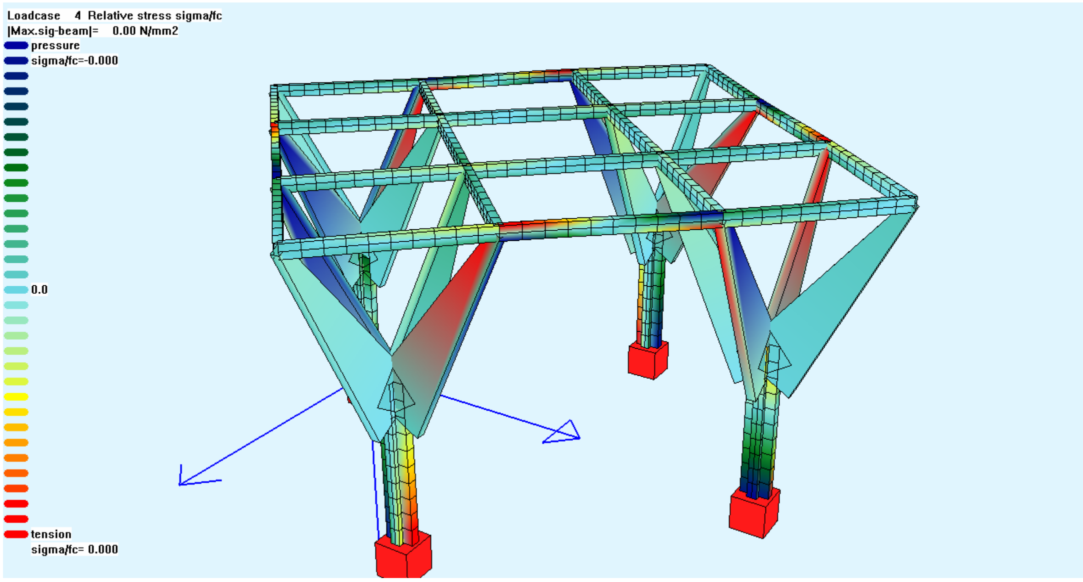


Fig 4.25 Visualization of the stresses induced by load case 4, Beaverton Library – enlarged version.

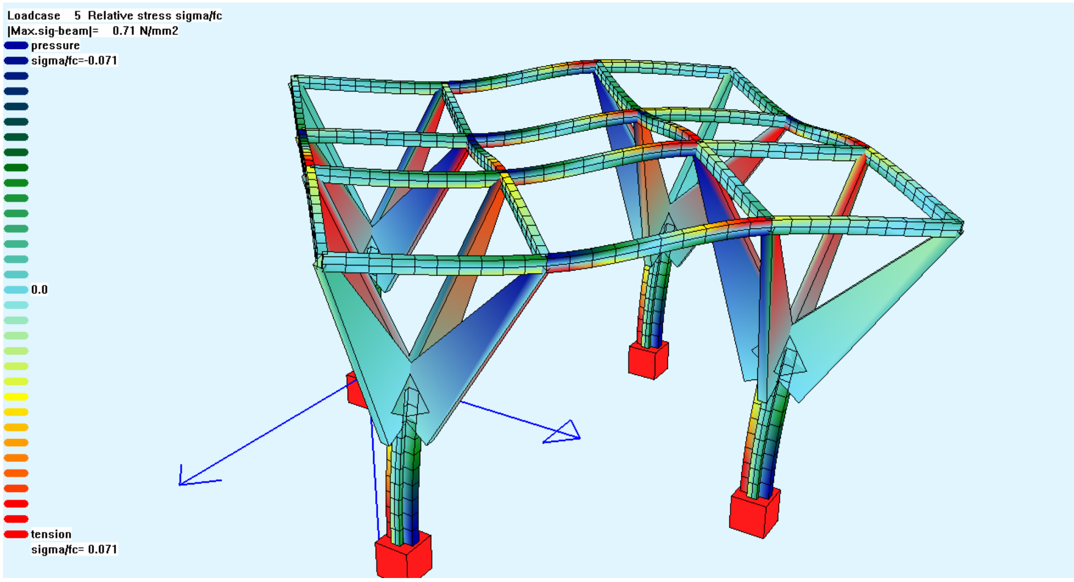
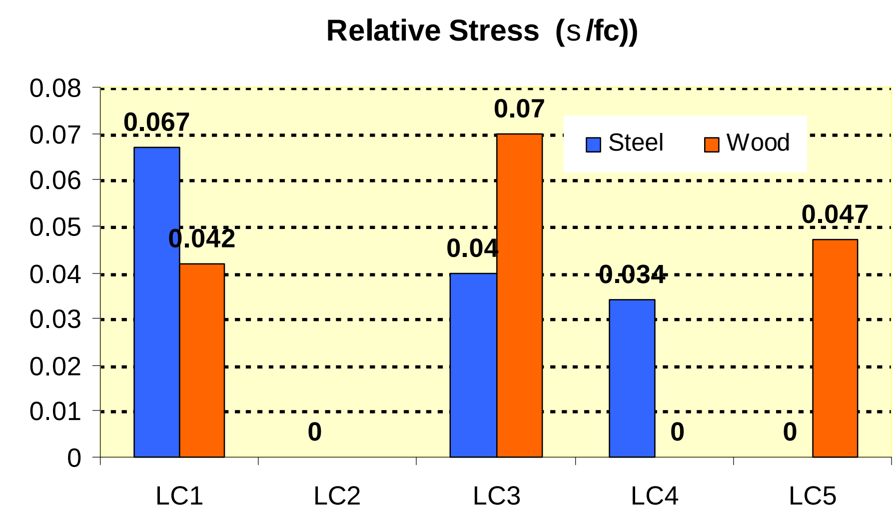


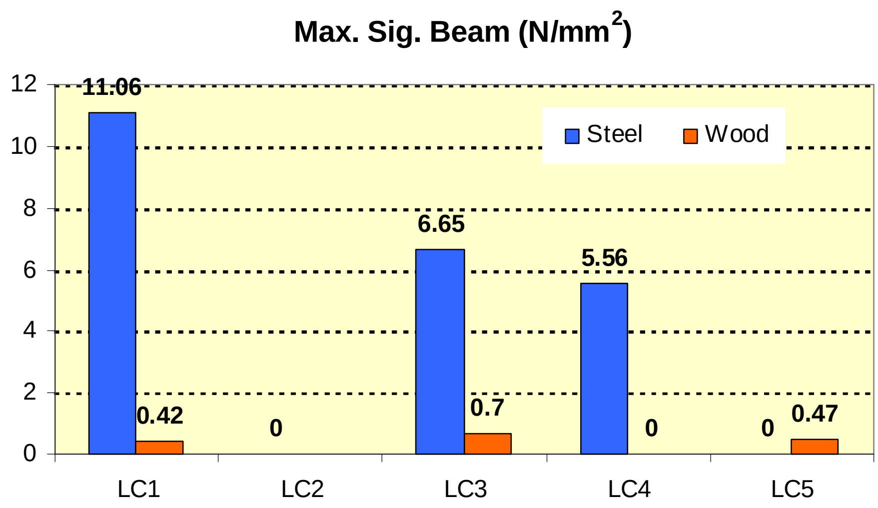
Fig 4.26 Visualization of the stresses induced by load case 5, Beaverton Library - enlarged version.

The following graphs illustrate that different materials (steel and glulam wood) have different performances in the structure. The overall relative stress (graph 4.8) is higher for steel in the load case 1, whereas for all other load cases it bigger for wood. It can be perceived that in the case of load case 4, and 5, the relative stresses for wood and steel, respectively are zero (0). This is due to the different predefined earthquake vibration directions. Different materials perform distinctively for different vibration directions. For example, in load case 4, wood is not sensitive to longitudinal vibration directions, whereas on load case 5 steel is not sensitive to vibrations along the x-axis (horizontal).

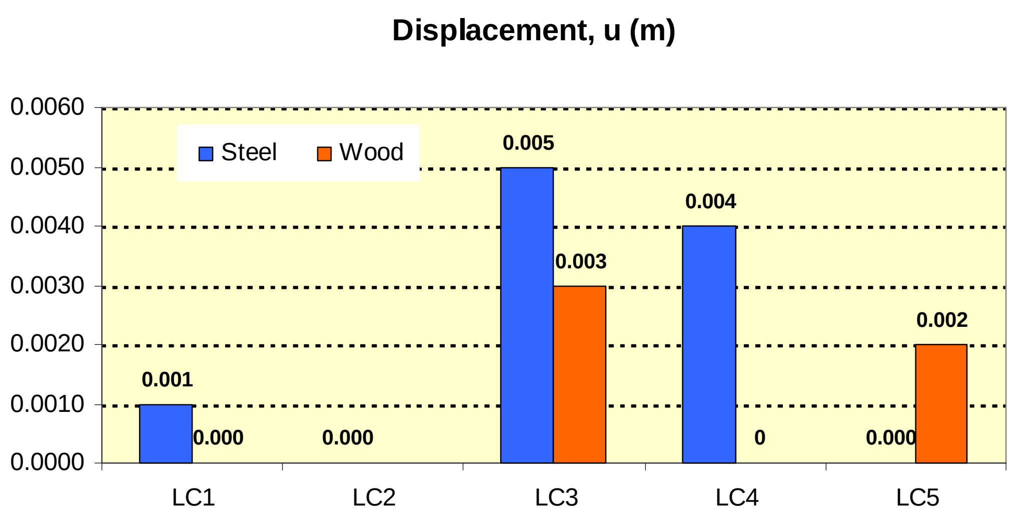


Graph 4.8 Comparison of relative stresses between Beaverton Library and hybrid Beaverton Stuttgart for different materials (wood and steel) – enlarged version.

The maximum sigma beam represents the maximum load supported by the structure per unit surface. The graph 4.9 shows that steel has greater resistance to heavier loads than wood, except in load case 5.



Graph 4.9 Comparison of the maximum sigma between Beaverton Library and hybrid Beaverton Stuttgart for different materials (wood and steel) – enlarged version.



Graph 4.10 Comparison of the deformation between Beaverton Library and hybrid Beaverton Stuttgart for different materials (wood and steel) – enlarged version.

4.9 Case 4: Therme Bad Oeynhausen – material comparison.

Therme Bad Oeynhausen was constructed originally with wooden rafters and concrete columns. For the purpose of material comparison, the original materials are going to be replaced by steel and all wood. The concrete columns will be replaced by tubular steel poles for the purpose of simulation.

4.9.1 **Concrete and steel**

Concrete and steel will be combined for the purpose of the comparative simulation. Steel will replace wooden rafters. The thickness of steel is one (1) cm.

The summary of the simulation results is presented in table 4.9.

Table 4.9 Structural simulation results for Therme Bad Oeynhausen, concrete and steel materials

Concrete-Steel-Steel Cable								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.322	17.93	0.002					
LC2					256.404			
LC3	0.066	2.03	0.001	0.217				
LC4	0.014	0.44	0	0.190				
LC5	0.128	4.32	0.001	0.188				
Model Parameters Concrete						15.365	2500	38412.5
Model Parameters Steel						21.472	7850	168555.2

The following screenshot represents the distribution of the relative stresses on the structure. The value of s/*fc* 0.322 shows that the structure is stable and that the displacements are minor, 0.002 meters.

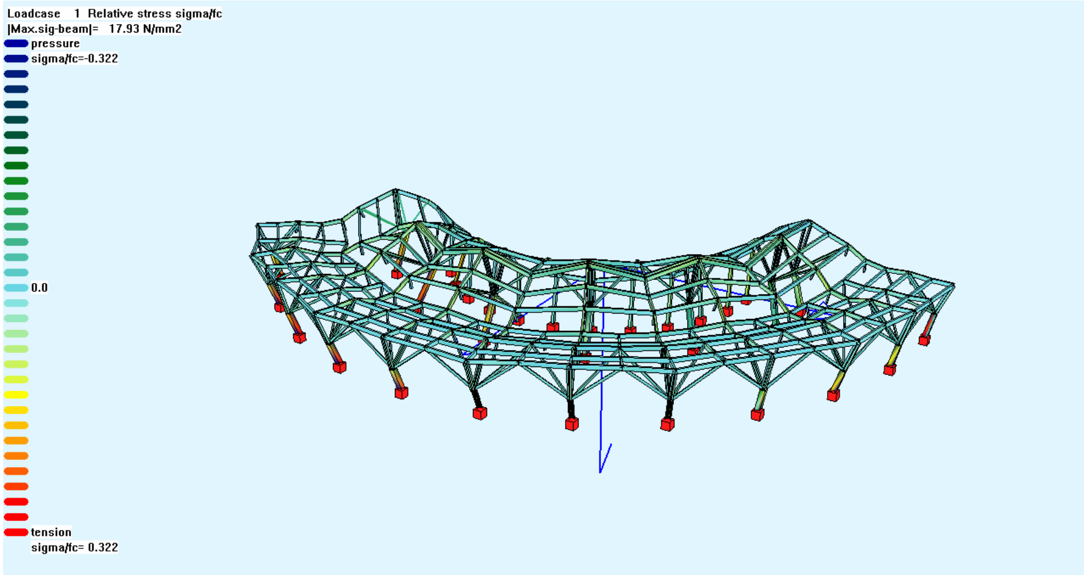


Fig 4.27 Visualization of the stresses applied to the Thereme Bad Oeynhausen structure under the sole influence of the dead load – concrete poles, steel structure.

The stability factor is 256.4 (fig 4.28).

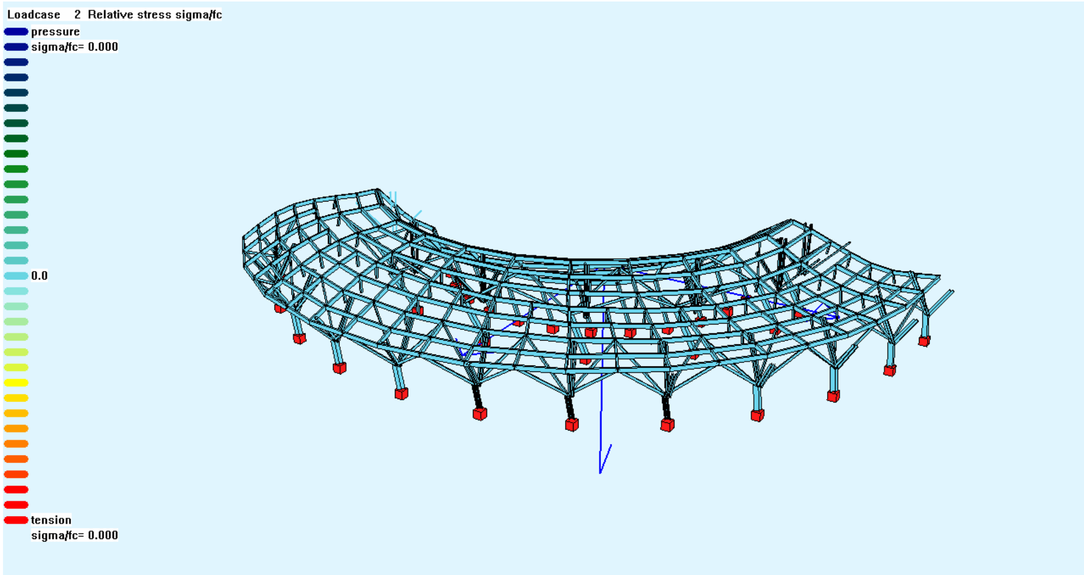


Fig 4.28 Visualization of the stability factor (load case 2), the case of concrete poles and steel structure.

Due to the circular geometry of the structure, the structure is not equally deformed (fig 4.29). The different direction of vibration results in different deformations on the left side of the screenshot as oppose to the right side. The relative stress is 0.066 indicating that the structure is stable and that very small displacements are expected, 0.001 meters.

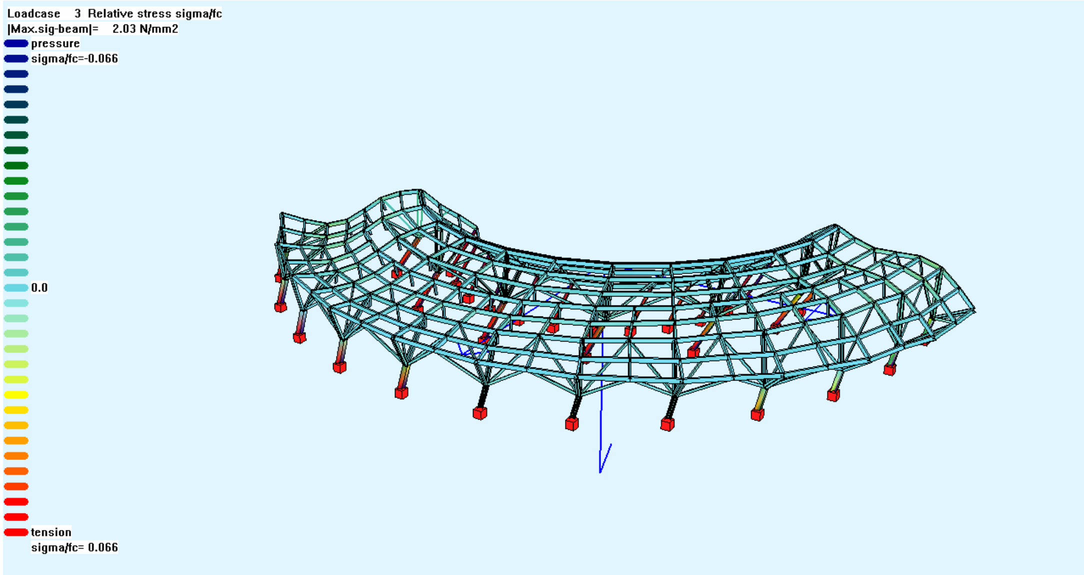


Fig 4.29 Visualization of the stresses induced by load case 3, the case of concrete poles and steel structure.

In fig 4.30, the opposite effect induced by the vibration of the earthquake can be visualized. The relative stress is 0.014, and the displacement is zero (0).

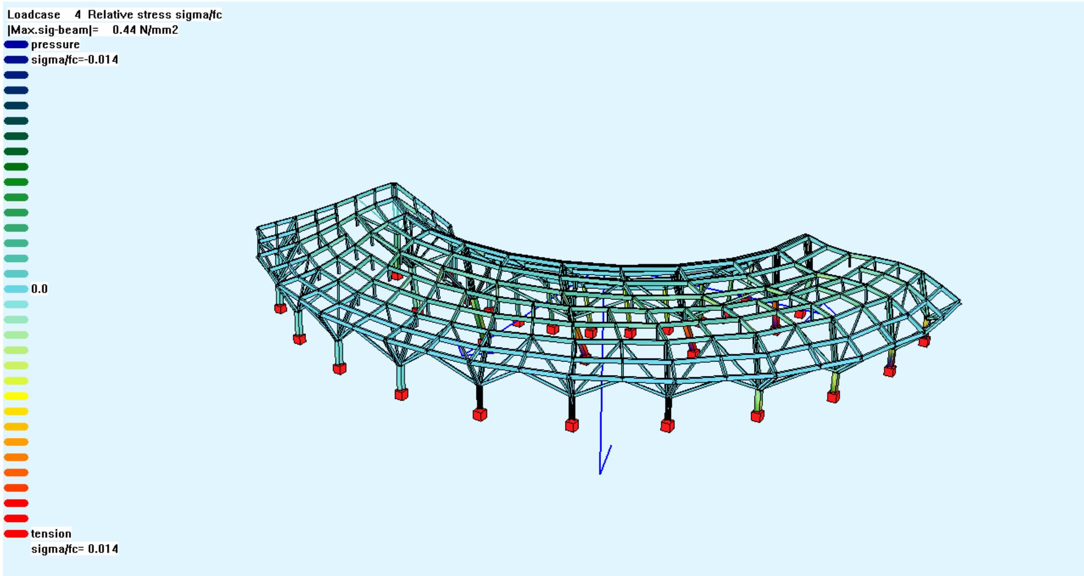


Fig 4.30 Visualization of the stresses induced by load case 4, the case of concrete poles and steel structure.

The following screenshot shows that the vibration is more homogeneous because of its longitudinal direction. Relative stress is greater in this load case 5, 0.128*;* however the structure is stable as the relative stress if far smaller than the limit maximum admissible stress for the material. The displacements are expected to be small too, 0.001 meters.

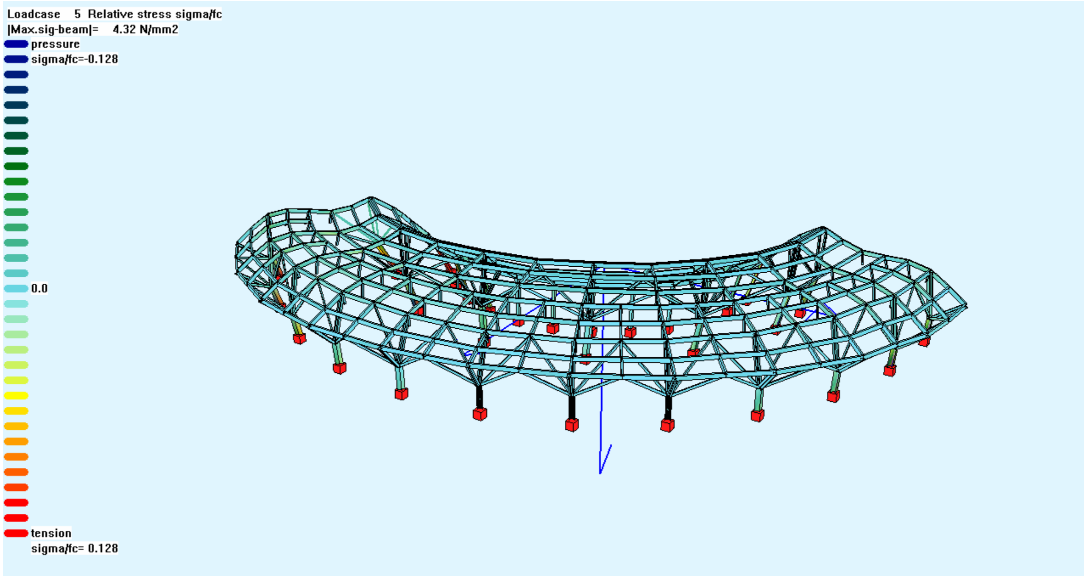


Fig 4.31 Visualization of the stresses induced by load case 5, the case of concrete poles and steel structure.

4.9.2 Steel

The following simulation is carried out only with steel materials. Concrete is replaced with tubular steel of 1 cm thickness, maintaining the same diameter of 50 cm on the centre part of the structure, and 30 cm on the sides of the structure.

Table 4.10 Structural simulation results for Therme Bad Oeynhausen, steel material

Steel-Steel-Steel Cable								
	Relative Stress, (s/fc)	**Max. s Beam (N/mm^2)**	**Displacement, u (m)**	**Period (s)**	**Stability Factor**	**Volume (m^3)**	**Specific Weight (kg/m3)**	**Weight, kg**
LC1	0.155	25.65	0.002					
LC2					279.548			
LC3	0.024	3.99	0.001	0.205				
LC4	0	0.01	0	0.182				
LC5	0.048	7.89	0.001	0.179				
MODEL PARAMETERS						22.41	7850	175918.5

Fig 4.32 shows that after replacing the concrete columns by tubular steel, the relative stress is further reduced to 0.155. Displacements continue to be minor, 0.002 meters. Smaller tension can be observed in the centre of the structure.

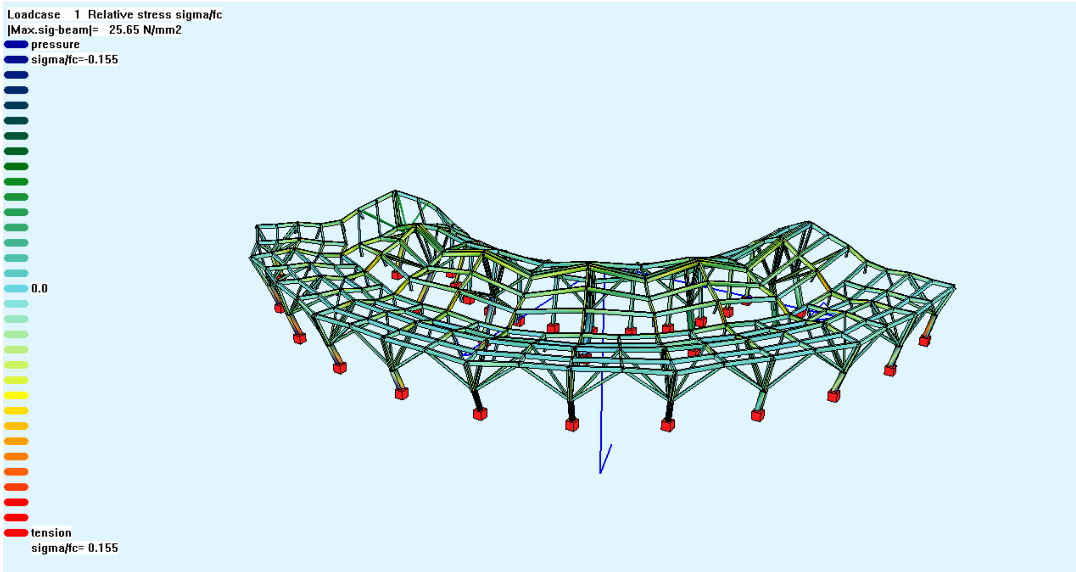


Fig 4.32 Visualization of the stresses applied to Therme Bad Oeynhausen structure under the sole influence of the dead load, the case steel poles and steel structure.

The stability factor is further increased 279.5.

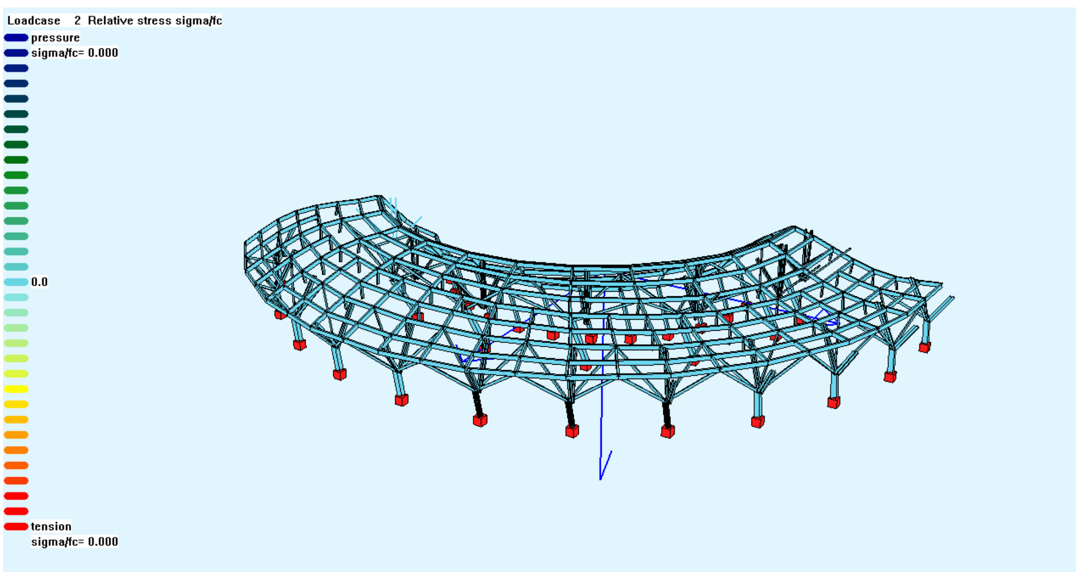


Fig 4.33 Visualization of the stability factor (load case 2), the case steel poles and steel structure.

Load case 3 results in lower relative stress of 0.024 (almost three times lower than with concrete and steel combination) and displacements are 1 mm.

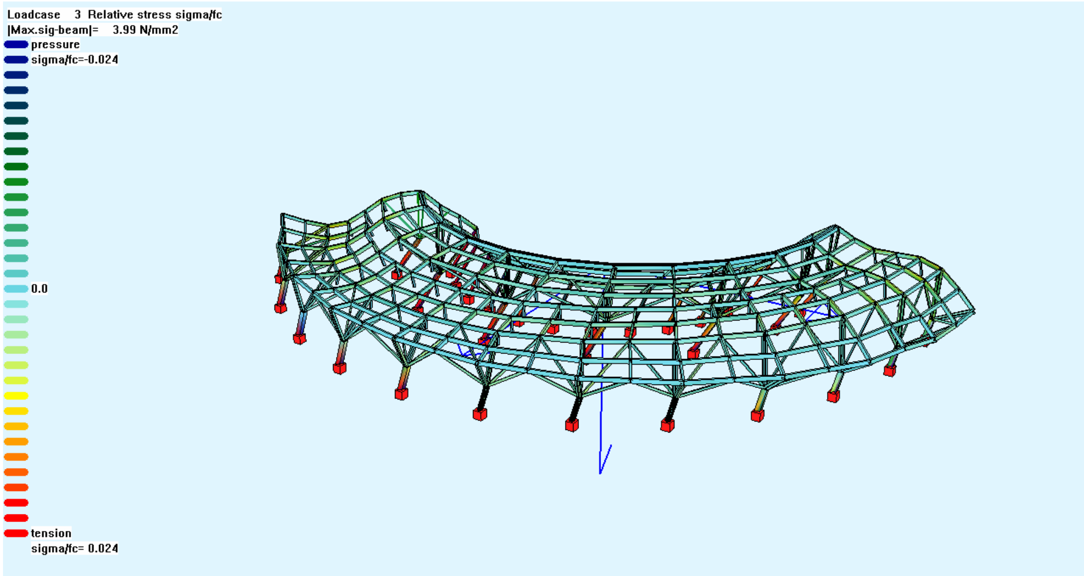


Fig 4.34 Visualization of the stresses induced by load case 3, the case steel poles and steel structure.

Fig 4.35 shows that earthquake has no effect on the structure. Displacement and relative stress are zero (0)

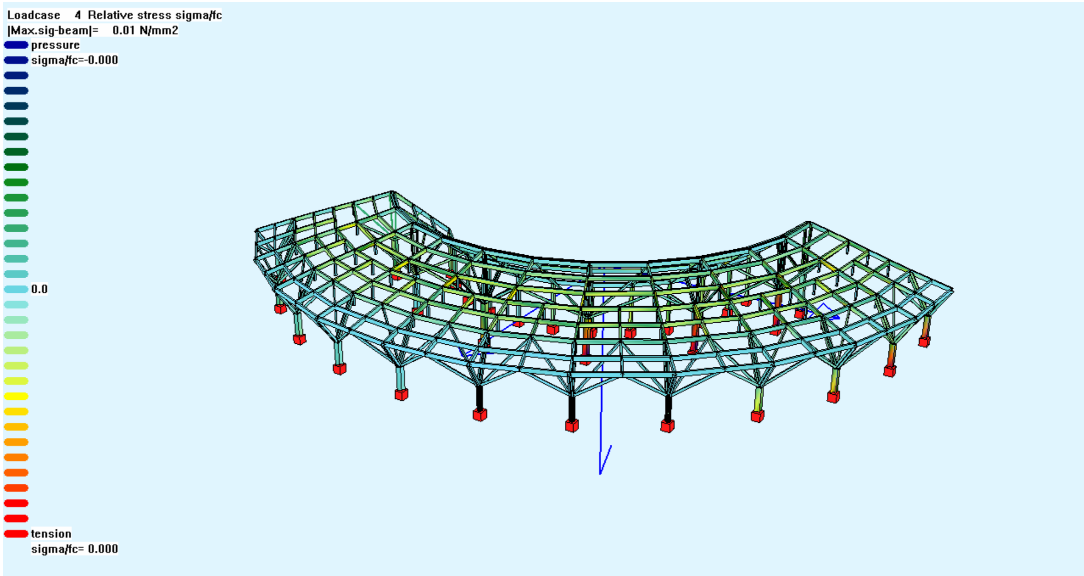


Fig 4.35 Visualization of the stresses induced by load case 4, the case steel poles and steel structure.

Figs 4.36 presents load case 5 earthquake deformations which have central direction. The relative stress is still 0.048 low for any serious deformation 1mm.

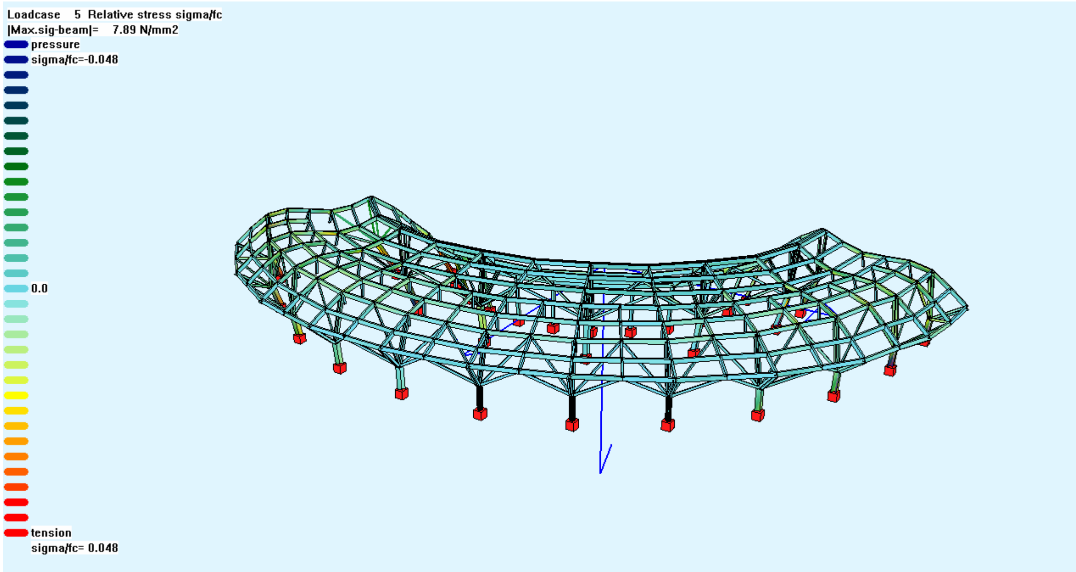


Fig 4.367 Visualization of the stresses induced by load case 5, the case steel poles and steel structure.

4.9.3 **Wood**

The following simulation is carried out only with wood materials. Original concrete columns are replaced with wooden ones maintaining the same cross section diameter of 50 cm on the central part of the structure, and 30 on the sides of the structure.

Table 4.11 Structural simulation results for Therme Bad Oeynhausen, wooden material

Wood								
LC1	Relative Stress, (s/fc)	Max. s Beam (N/mm^2)	Displacement, u (m)	Period (s)	Stability Factor	Volume (m^3)	Specific Weight (kg/m3)	Weight, kg
LC2	0.297	2.97	0.005					
LC3					89.791			
LC4	0.046	0.46	0.001	0.342				
LC5	0.018	0.18	0	0.318				
MODEL PARAMETERS	0.024	0.24	0.001	0.299				
						138.795	7850	1089540.8

The following screenshot (fig 4.37) illustrates the relative stress influencing the deformations of the structure. It can be observed that the deformations are approximately the same with as in fig 4.32, given that the relative stress and deformation values are a bit higher in this case, 0.297 whereas the displacement is 0.005.

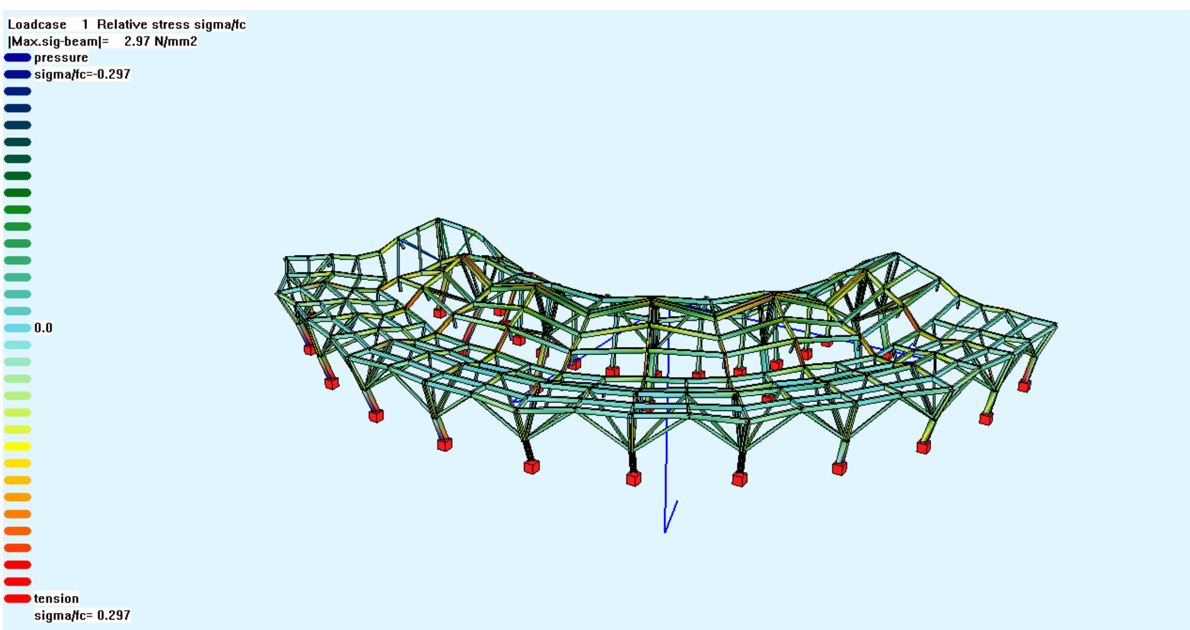


Fig 4.37 Visualization of the stresses applied to Therme Bad Oeynhausen structure, wooden structure.

The stability factor is the lowest in this case, 89,791, but yet the structure is highly stable to tolerate heavy loads (fig 4.38).

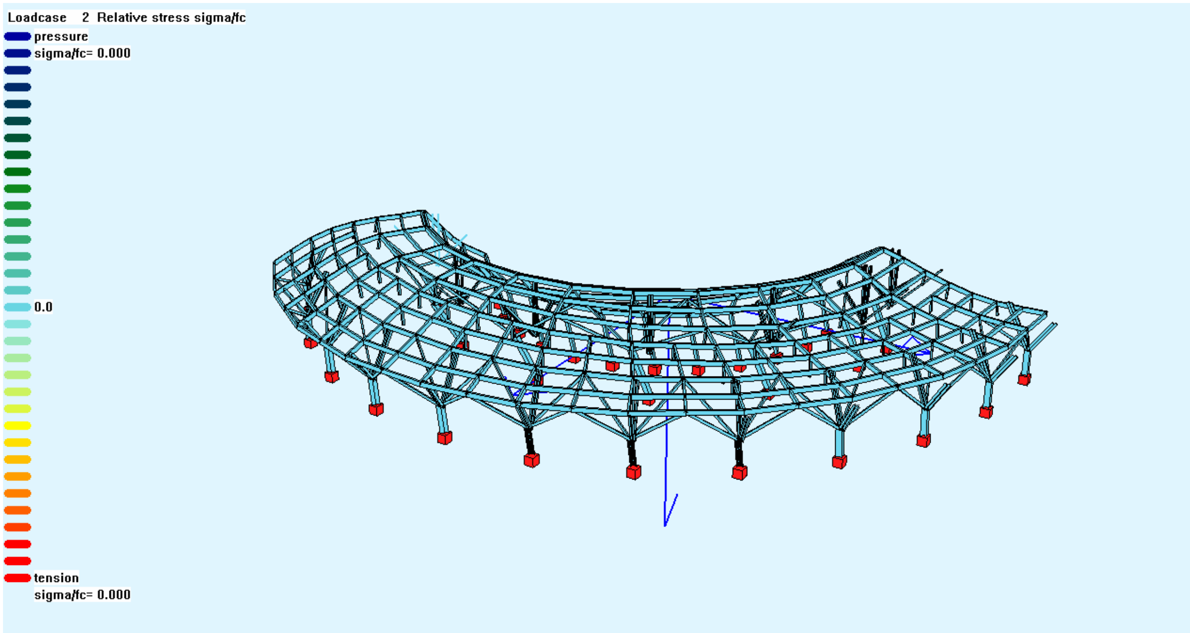


Fig 4.38 Visualization of the stability factor (load case 2), the case wooden structure.

Here we can observe that the centre of the structure has greater tension influence due to the standardized earthquake.

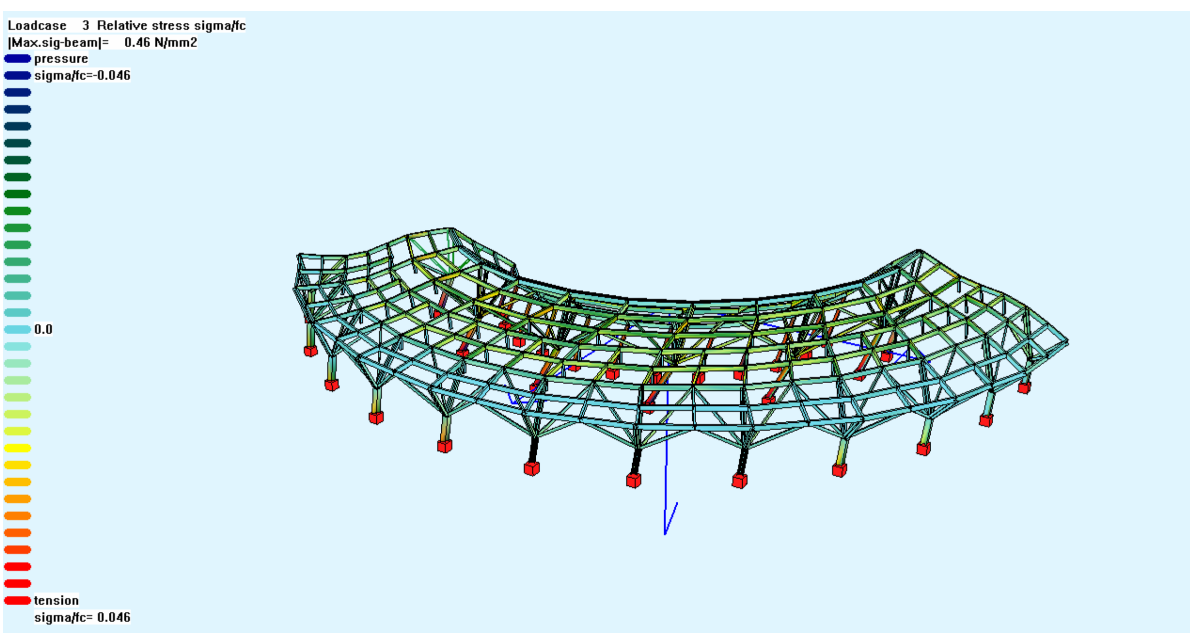


Fig 4.39 Visualization of the stresses induced by load case 3, the case of wooden structure.

It is interesting to note that the same structure morphology with different materials in particular load cases have different structural behaviour. The previous load case 4 for steel material (fig 4.35) shows that standardized earthquake has no influence in stresses, however in the next screenshot (fig 4.40), we can observe earthquake influence in deforming the structure to some extend. The relative stress continues to be low, 0.018 and the displacements is zero.

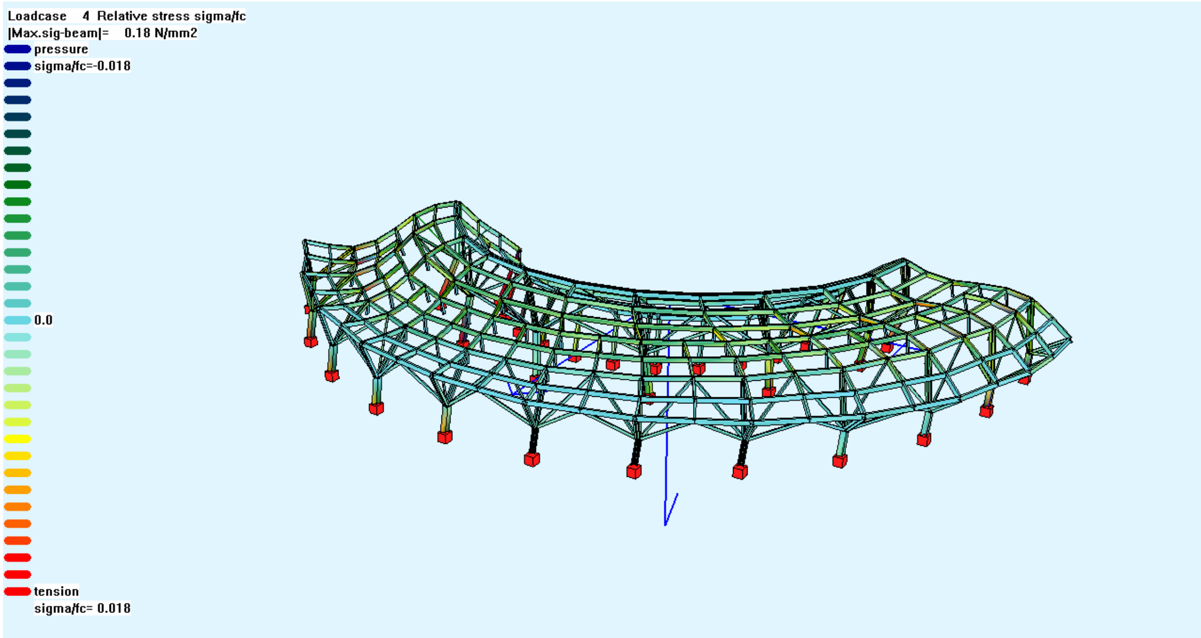


Fig 4.40 Visualization of the stresses induced by load case 4, the case of wooden structure.

The following screenshot (fig. 4.41) shows load case 5 deformations which are fairly similar to fig 4.37. However the relative stress relevant to this load case is smaller, 0.024.

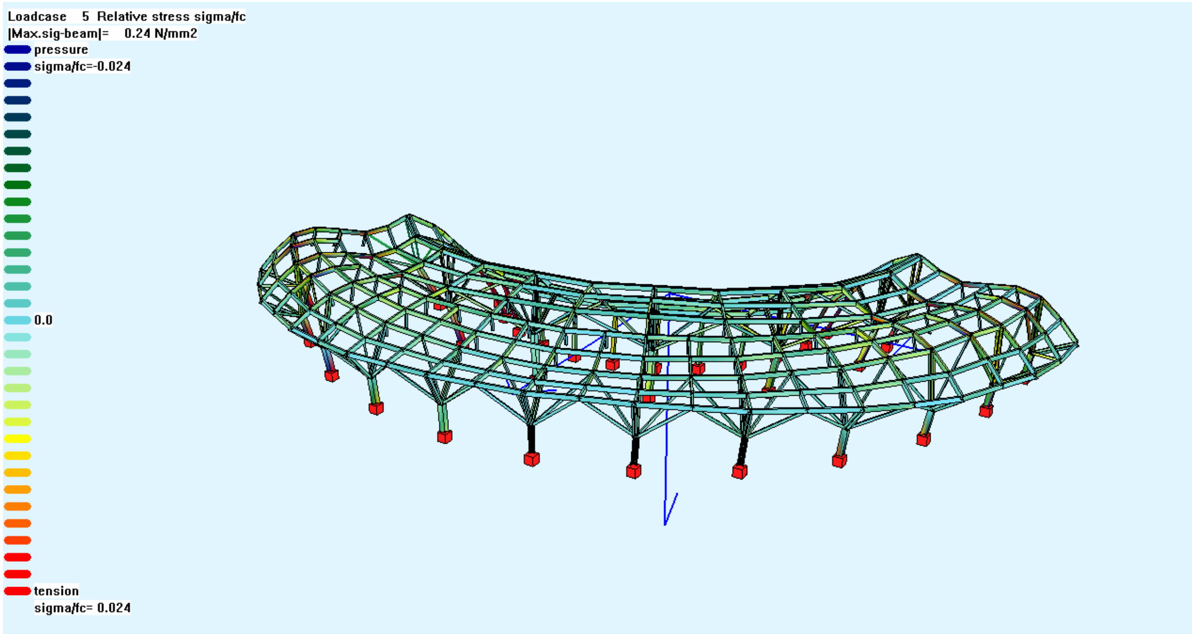
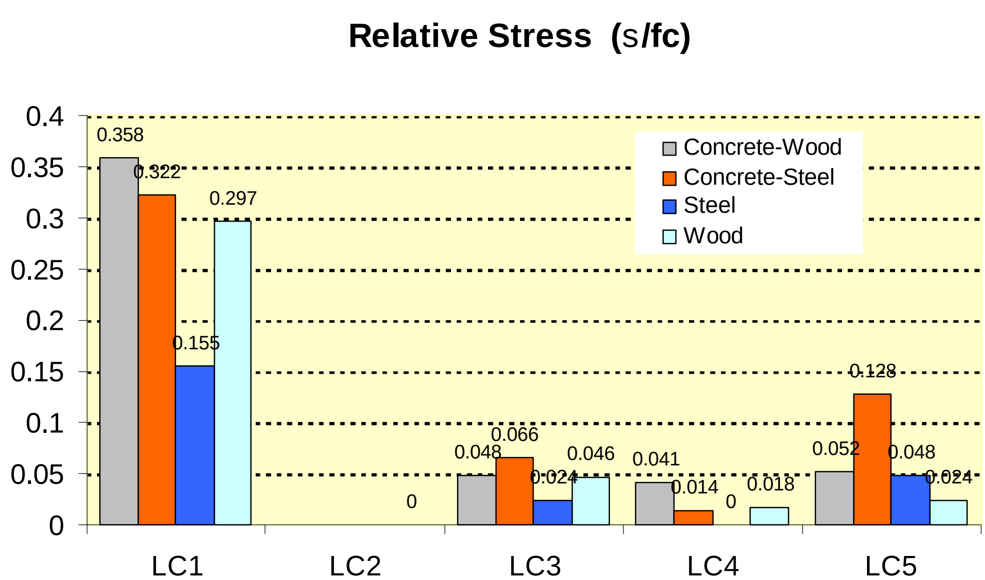


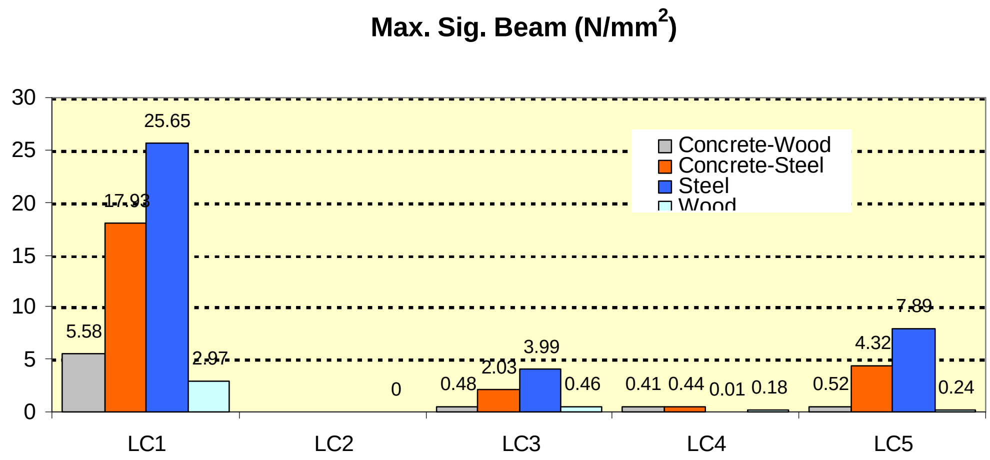
Fig 4.41 Visualization of the stresses induced by load case 4, the case of wooden structure.

Graph 4.15 represents the relative stress for a combination of materials for Therme Bad Oeynhausen. It can be concluded that the relative stresses are generally lower for the case of steel. Only in load case 5, wood induces the smallest stresses on the structure.



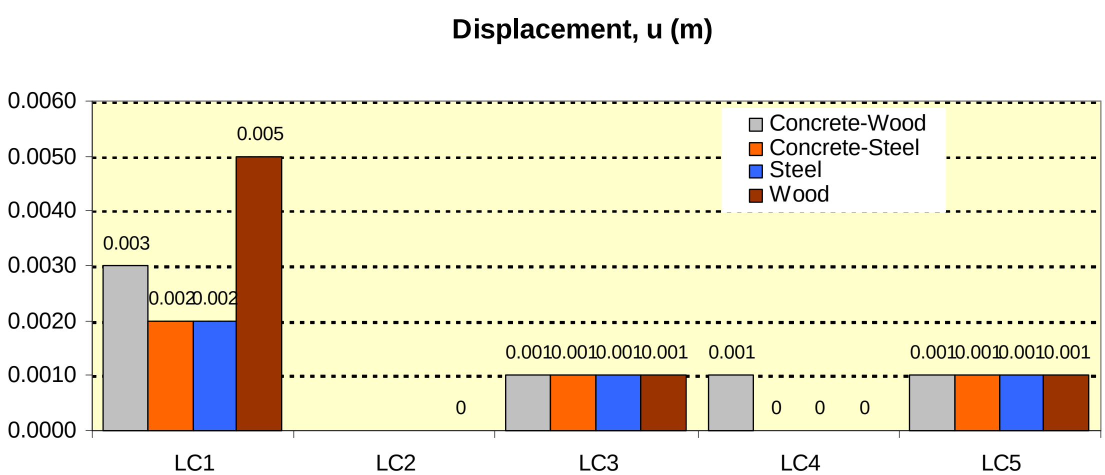
Graph 4.11 Comparison of the relative stress for Therme Bad Oeynhausen in three different materials concrete-wood, concrete-steel, and steel.

The value for the maximum load bearing capability is higher for steel and the lowest for wood.

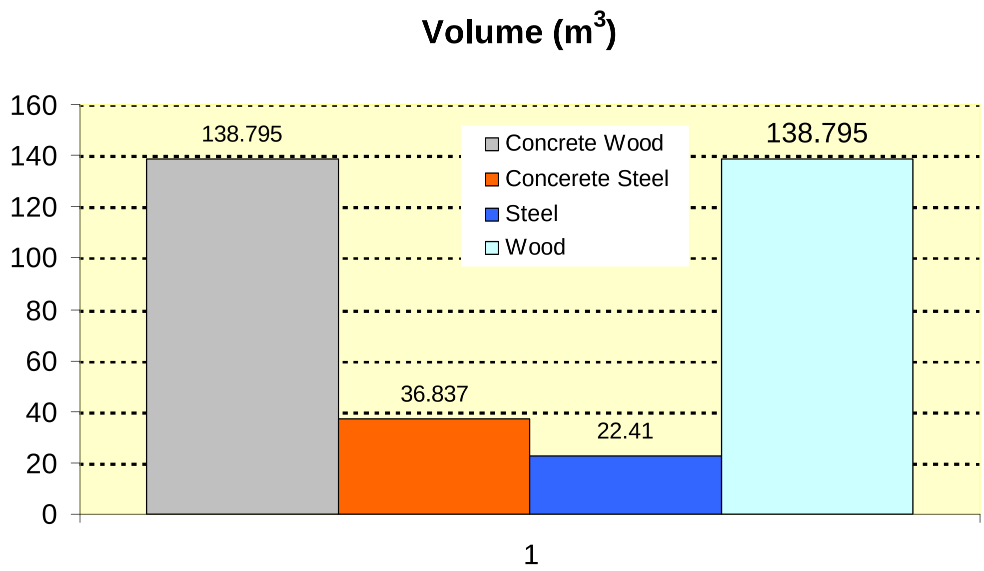


Graph 4.12 Comparison of the maximum sigma for Therme Bad Oeynhausen in three different materials concrete-wood, concrete-steel, and steel.

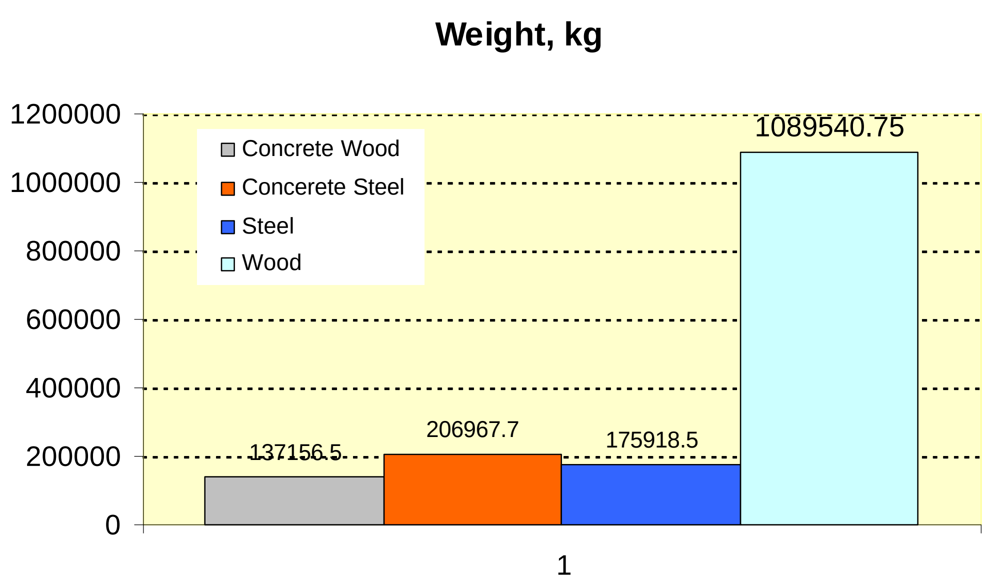
Except for load case 1, there are no significant differences among the combination of materials, concrete-wood, concrete-steel, wood and steel. The displacements induced are similar: in load case 1, wood shows the biggest displacement, 5 mm.



Graph 4.13 Comparison of the deformations in meters for Therme Bad Oeynhausen in four different materials concrete-wood, concrete-steel, wood and steel.

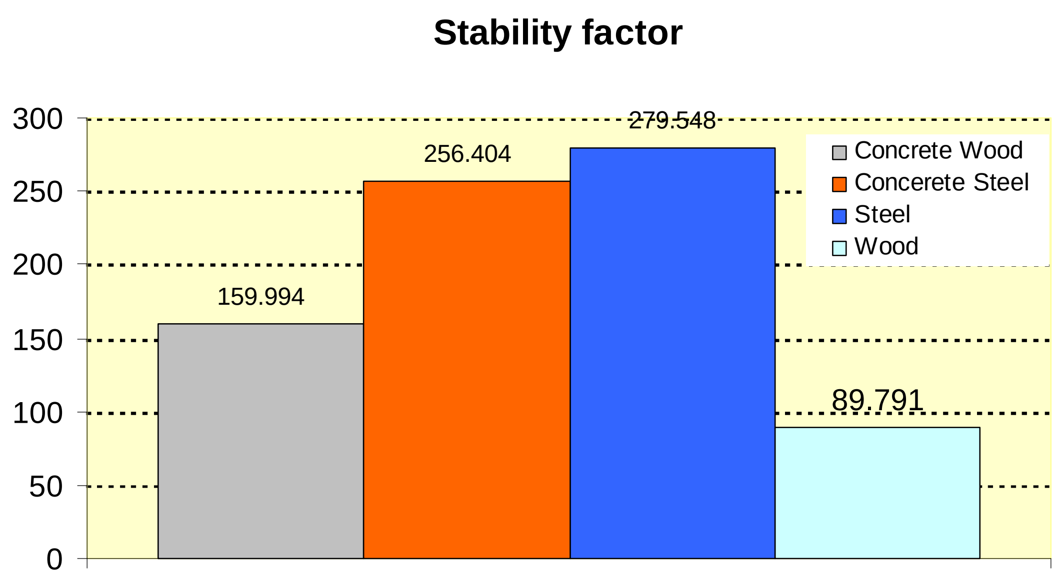


Graph 4.14 Comparison of the mass of materials, Therme Bad Oeynhausen.

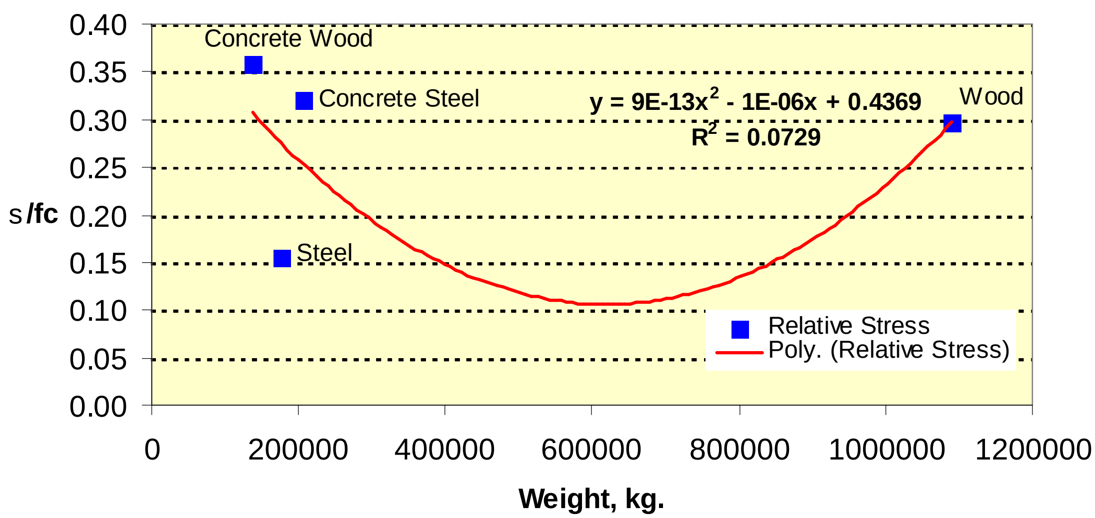


Graph 4.15 Comparison of the materials' weight, Therme Bad Oeynhausen.

The stability factor is higher for steel and concrete-steel cases. However, these cases represent relatively lower dead weights than wood and concrete-wood.



Graph 4.16 Stability factor for Therme Bad Oeynhausen, comparative analysis.



Graph 4.17 Comparative analysis of the relative stress as a function of the structure's weight (L1).

Steel is the most suitable material for Therme Bad Oeynhausen structure. In spite of its higher specific weight (7850 kg/m^3), the final structure has the lowest total weight and minimal stresses when compared with concrete and wood. This is due to the fact that steel profiles are hollow, while wood and concrete are massive and therefore increase the total weight.

4.10 Discussion

A summary of the main BUILD simulation results is presented in the next table.

Table 4.12 Summary of BUILD simulation results for all case studies.

Case Study	Relative Stress, (s/fc)	Max. Sig. Beam (N/mm^2)	Displacement, u (m)	Stability Factor	Volume (m^3)	Weight, kg
Stuttgart Airport - Steel	0.678	111.87	0.098	43.879	12.383	97206.55
Stuttgart Airport - Wood	1.847	18.47	0.316	15.771	64.835	51868
Beaverton Library - Glulam	0.042	0.42	0	277.361	27.384	21907.2
Hybrid Beaverton - Stuttgart - Steel, reduced version	0.033	5.39	0	549.97	1.297	10181.45
Hybrid Stuttgart - Beaverton - Steel, increased version	0.067	11.06	0.001	270.383	2.19	17191.5
Hybrid Stuttgart - Beaverton - Wood, increased version	0.061	0.61	0.001	186.073	89.43	71544
Therme Bad Oeynhausen - Concrete - Wood - Steel Cable	0.358	5.58	0.003	159.994	138.8	137156.5
Therme Bad Oeynhausen - Concrete - Steel	0.322	17.93	0.002	256.404	36.837	206967.7
Therme Bad Oeynhausen - Steel	0.155	25.65	0.002	279.548	22.41	175918.5
Therme Bad Oeynhausen - Wood	0.297	2.97	0.005	89.791	138.8	1089541

The work performed on lightweight structures analysis resulted in the following conclusions:

(a) Case 1: Stuttgart Airport

The Stuttgart Airport was originally designed with steel material. The same structural morphology in wood demonstrates that the structure would not be stable because the stress induced by the applied load is 85% above the maximum admissible stress. In fact, it exceeds the factor of safety, or the ratio of maximum stress that a structural member can withstand. The materials will enter the plastic range, with irreversible deformations to the structure and possible structural failure (fracturing, buckling, and collapse). The hypothetical structural assembly in wood would be incapable to sustain the load bearing functions for which it was originally designed.

(b) Case 2: Hybrid Beaverton Stuttgart

The hybrid Beaverton-Stuttgart simulated with steel, demonstrates a better structural performance than the original Beaverton Library, constructed with wood material. Although the wood material exhibits higher deformations, they are of the same order of magnitude as for steel material. However, the maximum load bearing capacity for steel is 12.8 times higher than for wood and stability factor twice as high.

(c) Case 3: Hybrid Stuttgart-Beaverton

When increasing the dimensions of the hybrid Beaverton-Stuttgart to the equivalent of Stuttgart's dimensions, steel is the material that exhibits the highest value for the load bearing capacity (26 times higher than that of wood for LC1) and for the stability factor, and the smallest volume and mass. This is a desirable property for lightweight structures.

(d) Case 4: Therme Bad Oeynhausen

The best performing material for Therme Bad Oeynhausen structure is steel. Although its specific weight is higher (7850 kg/m^3), the final structure exhibits the lowest total weight, the highest value for the maximum load bearing capacity, higher stability factor and smaller stresses, when compared with concrete and wood.

The main aim of lightweight structure is to reduce the mass of the material and at the same time introduce geometric efficiency to provide maximum load capacity. Steel is widely used for lightweight constructions. However, its specific weight is 7850 kg/m^3 compared to 800 kg/m^3 for wood and 2500 kg/m^3 for concrete. Surprisingly, in the comparative analysis for the Therme Bad Oeynhausen, steel is the best "lightweight" material. The overall steel structure has the lowest weight for the same morphology.

5 Conclusions and suggestions of future work

A way of "lightning" a building structure is to remove inefficient mass, while reinforcing the structure in other places. For steel structures, due to the high density of the steel material and additives composing the steel alloys (manganese, silicon, chromium and others) influencing the quality of the steel, it can be possible to remove inefficient mass, creating hallow steel tubes, without decreasing the steel's reinforcing capability. This is not possible for wood and concrete.

For all the case studies, it is shown that steel is the material exhibiting the highest load bearing capacity and simultaneously the smallest volume and mass. Therefore, steel is the best performing lightweight structure, in spite of having higher specific weight.

The work in this thesis can be further developed by testing the structural performance of different innovative materials, such as composite fibre materials. It is also of importance to assess the environmental impact (in terms of energy densities embodied in the structures) of the different material options.

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