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On plastic development of timber structures based on 3D interactive vector-based graphic statics (VGS)

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Abstract

The present contribution addresses both the topics of the design of timber-to-timber joints and the design of innovative and structurally efficient timber structures with the aid of a computational tool based on vector-based graphic statics (VGS).

First, this manuscript explains how the latest developments of graphic statics and its use applied to both timber joints and structures can improve the design of structures made of this low embodied carbon material. An exhaustive review of timber assemblies focussing on their sustainability and their structural behaviour is presented. Among these is the notch joint specifically identified in the context of digital fabrication and circular use of timber.

Afterwards, the theoretical framework of this research is explained. Taking advantage of the lower bound theorem of the theory of plasticity, the main hypotheses that enable the use of graphic statics and strut-and-tie modelling (STM) for timber are then presented. In addition, the structural behaviour of the single notch joint is evaluated using algebraic dimensioning method. The limitations of this method are pointed out and the article proposes an integrated universal approach to investigate the problem using Strut and Tie Modelling (STM) and stress fields. The results of this theoretical framework are validated through 1/1 scale lab tests. Finally, the third chapter illustrates the potential of VGS via a Research-by-Design approach. In the aim of testing if designing simultaneously creative and efficient timber structures could be effective while using the VGS, architectural engineering students were asked to focus on both the primary load-bearing structure and the joint-systems.

Keywords Timber construction, Structural design, Digital fabrication, Parametric design, Graphic-statics, VGS, Research-by-design, Teaching of structural design

1 Context and scope

1.1 The design of structures as a multi-factorial problem

The design of load-bearing structures is a multi-factorial exercise that requires a permanent anchoring in the physical context of the project. In addition to ensuring the mechanical resistance of the structure, the design needs to consider many different factors such as functionality, geometry, construction, maintenance, cost, and environmental impact among others. In a world of limited and dwindling resources, the structure should also be designed taking into account the possibilities of disassembly, recycling, and reuse of its components.

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Within such a context, a structural solution might only prove optimal regarding the importance given to each criterion. Consequently, the first challenge lies in defining the parameters of comparison and their respective weighting. Architects are used to dealing with project involving a set of complex and different constraints whereas structural efficiency might often left aside. The methodology presented here aims to give a simultaneous focus on both the structural and architectural requirements.

1.2 Graphic statics and the design of structures

1.2.1 Development of graphic statics

Regarding the design and analysis of structures, graphic statics has proven its considerable potential for achieving efficient and elegant structures. This method relies on two interdependent diagrams, namely the form and force diagrams (Maxwell 1864). The first represent the geometry of the structure together with its external forces, the latter embeds a synthetic vector representation of the forces applied to each node of the structure, thus representing vectorially the equilibrium of forces acting on the structure.

The interdependency of the two diagrams and their visual convenience provides a visual and intuitive understanding of the relationship between a structural shape and its inner stresses. The Swiss engineer Robert Maillart is one of the pioneers using graphic statics to define innovative and efficient structures. An iconic example is the Salginatobel Bridge built in 1929 (Fivet and Zastavni 2012) This method relying on hand-drawing was almost abandoned in the second half of the twentieth century, partially, due to the development of computers and numerical tools (Figs. 1 and 2).

1.2.2 Resurgence of the Interest of graphic statics

The significant resurgence of interest for graphic statics among engineers, architects and researchers in the last years can somehow be summarized as follow. Numerical analysis approaches are not the best suited for the early stage of design since their way of working relies more on an analytical process and structural models requiring several hypotheses to give a result, resulting in a lack of interactivity.

Furthermore, the possibility to benefit from a computational framework to use graphic statics created a



Fig. 1 Salginatobel Bridge (1929) from Robert Maillart, picture taken by D. Zastavni (2022)

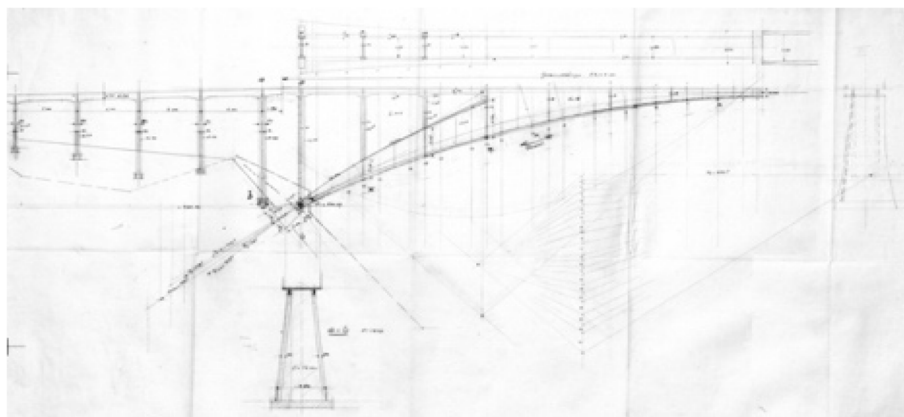


Fig. 2 Salginatobel Bridge (1929) from Robert Maillart, static drawing: with form diagram on the right

favourable context, since hand-drawing can be very time consuming, require a specific and precise knowledge and lack interactivity since they cannot quickly generate or modify geometries for a project.

Finally, the latest theoretical and practical development of 3D graphic statics opened new possibilities in terms of complex 3-dimensional structural typologies. In this, two main methods were developed, namely the vector-based (D’Acunto et al. 2019) and the polyhedral-based (Akbarzadeh 2017); (Lee 2018). Both approaches have their own specificities and benefits (Fig. 3).

1.2.3 VGS-tool, a computational tool for 3D vector based graphic statics

VGS is a plugin in the digital environment of Grasshopper from McNeel Rhinoceros whose main purpose is to automatically generate 3D vector-based interdependent form and force diagrams. VGS is developed by Pierluigi D’acunto, Jean-Philippe Jasienski, Yuchi Shen and Patrick Ole Ohlbrock. The theoretical foundations are based on vector-based graphic statics (D’Acunto et al. 2019) and its implementation results in a computational tool (Jasienski 2023).

The plugin allows the designer to generate 3D structures in equilibrium, as well as to modify them in real-time acting either on the force or the form diagram (while assessing the consequence of the modification on the other diagram). It represents a very adequate tool for the generation of efficient structures at equilibrium at the very first stages of the design phase (Fig. 4).

1.3 Timber as a construction material for the present and the future

1.3.1 Timber for spatial structures composed of bar elements

The current environmental crisis requires a major reduction of our CO2 emissions to limit the effects of global warming. In this context, structural engineers have an important role because the construction industry generates around 40% of gasses inducing GW and 36% of the waste in Europe. It is important to highlight that the primary structure of buildings represents more than 50% of this impact. In order to achieve the goals fixed by the 2015 Paris agreement, the construction industry needs to be carbon-free by 2050. On top of that, the increase in population calls for building new dwellings. Both engineers and architects are facing a huge challenge to find new ways of building that drastically reduces the ecological impact.

In this context, timber appears to be a very interesting material because it has the capacity to store CO2 resulting in a lower carbon footprint compared to other materials. The negative Global Warming Potential (GWP) calls it to play a major role as a construction material in the coming years. In this perspective, VGS is inherently adequate to support the analysis and design of both joints and spatial networks of bar elements in static equilibrium. This feature fits particularly timber structures which are characterized by such arrangements. Here below, we will highlight the different kind of joints which allow the composition of such frameworks.

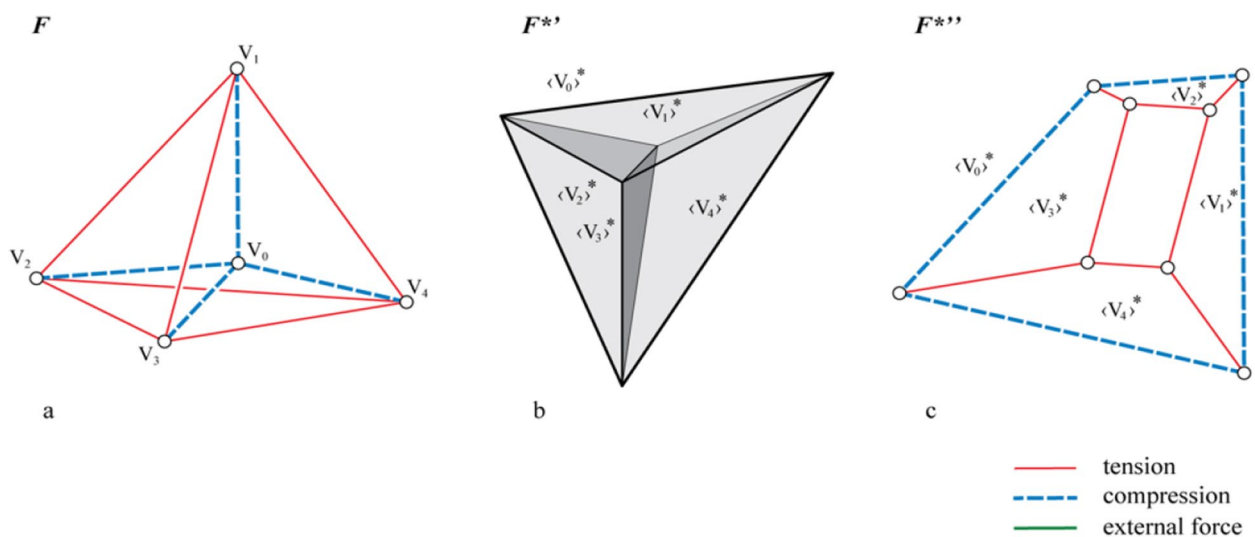


Fig. 3 Graphic statics in 3 dimensions: Form diagram F of a self-stressed tetrahedron (a)—polyhedral based force diagram (b)—vector-based force diagram (c) (from D’Acunto et al. 2019)

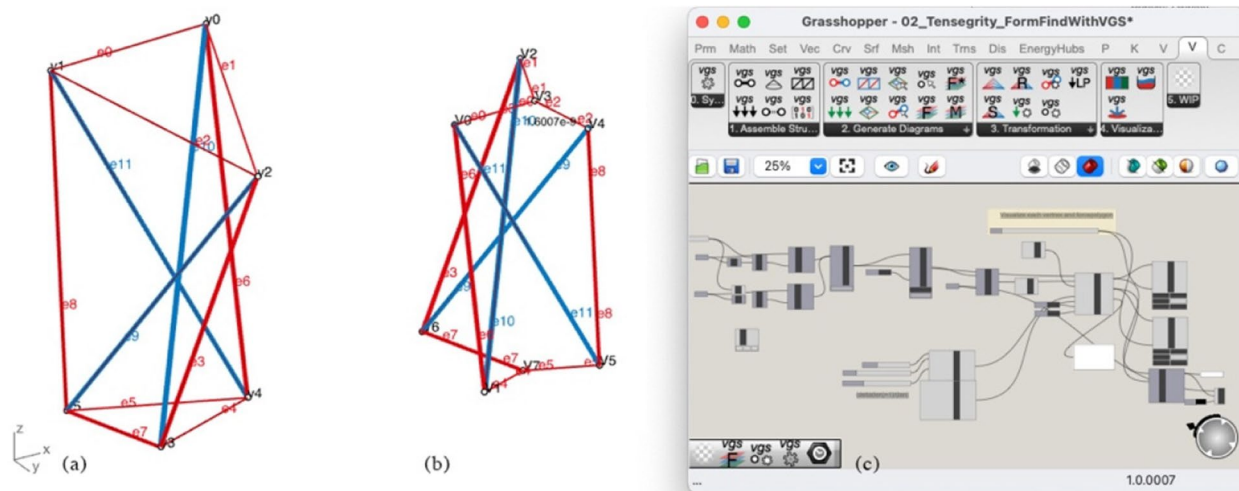


Fig. 4 View of a structural model of a 3D tensegrity structure in the VGS tool (Jasienski 2023) within the McNeel Rhinoceros and Grasshopper digital environment (McNeel 2023). From left to right: Form diagram (a), corresponding Force Diagram (b), parametric definition with the VGS modules in Grasshopper (c)

1.3.2 Review of joints in timber

The geometry of timber joints evolved over time and depending to their specific use. In the western world, and if we exclude stacked constructions using a compression-working structural system such as stacked log-constructions, the main joint types can be distributed into the following categories: metal plate connectors, rod-type fasteners associated or not to steel plate gusset, contact joints. The two latter systems have their historical counterpart as traditional connection by mortise and tenon in half-timbering for example and as carpentry notched joints. Two specific Eastern joints as Chinese bracket system and Japanese complex framing joints as Shi-ho-shachi-kumi-te (connection by tenon and wedged pin) are also presented in this review.

All these systems are briefly explained below and examined from the point of view of their relevance in terms of sustainability and potential use for digital fabrication, focusing on small to medium structures.

Punched metal plate fasteners are made of metal plate having integral projections punched out in one direction and bent perpendicular to the base of the plate. Available from the 1950's, they are used to join two or more pieces of timber of the same thickness in the same plane and are suited for the prefabrication of trusses. They are pressed directly into the timber elements to a depth corresponding to approximately 1/3 of the thickness of the assembled timber elements. Despite their great efficiency, these systems are sensitive to fire and are not dismantlable. They will not be considered below.

Cold-formed steel fasteners as joist hangers, framing anchors and other fasteners made from cold-formed

steel have widely replaced traditional carpentry joints. Although they can be easily dismantled with limited damage to the structural elements, they remain sensitive to fire and have limited capacity to withstand heavy loads and water-related stresses. More efficient systems consisting of thick machined steel elements may not have these disadvantages. As with the previous category, they will not be considered in the following analysis.

Rod-type fasteners: nails, screws, bolts, and dowels are mainly associated respectively to shear joints or with steel plate gusset and special connector devices. Shear joints with rod-type fasteners can be used for timber-to-timber joints, panel-to-timber joints, or steel-to-timber joints. These systems are efficient for limited loads and the resulting calculations are simple (checking the shear of the rods, the diametral pressure on the timber, and avoiding block breakage), although they remain sensitive to damage in the event of fire or earthquake. Rod-type fasteners associated to pre-drilled metal plates used as central or lateral gussets are used when it is about to raise the loading capacity of timber assemblies. Even if this represents the most common way to develop a safe high-bearing capacity connection in timber, disassembling and reassembling such structure involves a lack of bearing capacity and partial damaging. These connections are also irreversibly damaged by earthquakes and local overloading.

Frame corners with rod-type fasteners as dowels open the possibility for larger structural member to develop moment-resisting joints once dowels are adequately disposed on a circle at the same distance of a common centre of rotation.. They do not represent a specific issue

about calculations since the possible failure modes are clearly described in corresponding calculation codes. Nevertheless, these connection-joints may appear unnatural since dowels develop forces parallel or perpendicular to wood grain depending of their respective position, allowing a possible fragile breakage acting in tension perpendicular to grain... Additionally, moisture changes involving shrinkage are an additional risk whose magnitude is proportional to the dimensions of structural members blocked into the joint area.

_Notch joints (sometime named “timber-to-timber joint”, or “Frame joints”) are contact joints that are the traditional way to assemble structural members. They are also usually met as high-capacity timber joints that implement multiple-contact notches with resin locking zones, in modern structures. Such joints involve direct contact of the extremity of an inclined member against another to which compression forces are transmitted. Typical applications are connections between a main rafter and tie-beam or at angles of braced beams. In some specific cases tractions forces can be transmitted by direct contact depending on the interplay of connecting notches (as between main rafters and king post in a roof truss e.g.). Traditionally, pieces are maintained in contact by inserting a skewed protruding tenon at the end of the strut into a groove, named mortise, in the connected member. Finally, the joint is locked by a unique hardwood peg inserted through both pieces. Currently tenon and mortise are avoided to simplify the construction and the geometry of the contact plans, sometime associated with screws, is sufficient to maintain contact. These joints present several advantages:

- possible avoidance of steel connectors
- less likely to lose their load-bearing capacity in the event of an earthquake
- possible to easily disassemble and reassemble without loss of performance
- suited for digital fabrication

For these reasons, this category of joints was selected for the research presented below.

_Traditional Chinese bracket system is the ingenious arrangement of crossed short timber segments of increasing lengths placed at the top of columns to connect them to a beam system with successive corbelling. They work thanks to dead weight and balancing forces that develop a kind of smooth but adaptable embedding. As other eastern joint systems, they suffer little of earthquake, do not involve steel and can be fully disassembled and reassembled without loss of load-bearing capacity. They nevertheless present a certain complexity that require skilled craftsmanship and high-grade

timber, are limited to post-and-beam connections and have a limited load-bearing capacity (Fig. 5).

_Traditional Japanese framing joints are connection systems using a complex tenon systems at the end of beams to connect them to posts. The joints action is driven by the direct support acting in compression through mortise for vertical loading, and the bending capacities developed by tenons, once locked by hardwood keys or pins, against horizontal loading. Alongside this, the roof structures use the same type of assembly or stacking and corbelling systems. These joints require both high-grade timber without nodes and skilled craftsmanship in their fabrication and assembling. They do not involve steel and can be fully disassembled and reassembled without loss of load-bearing capacity. A modern version of these principles has been implemented in the form of steel connections systems, as *Janebo* system (Schwaner, 1997 – see Fig. 6) for instance, although with less capacity to withstand bending moment forces.

_Glued joints are sometime used for connections in large truss structures. These are stiff connections having the disadvantage of this performance: behaviour is quite rigid when transmitting forces resulting in poor possible redistribution of forces close to collapse stage and nodes structures that can hardly be disassembled.

Tree structural actions mainly govern the specific families of timber joints: shear inside steel rod and metal-sheet connectors; bending forces inside traditional eastern joints; tension/compression/shear in notch joints. Even though these are not the only forces they can cope with as nearly all actions can also be met

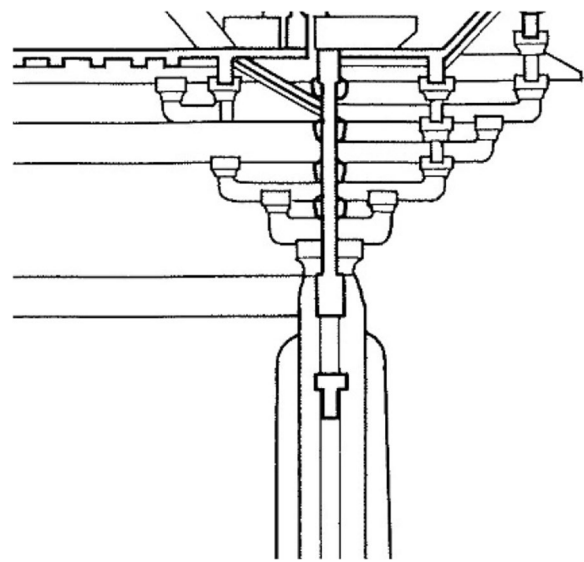


Fig. 5 Columns head in Guanyin ge, Jixian (Stierlin, 1977)

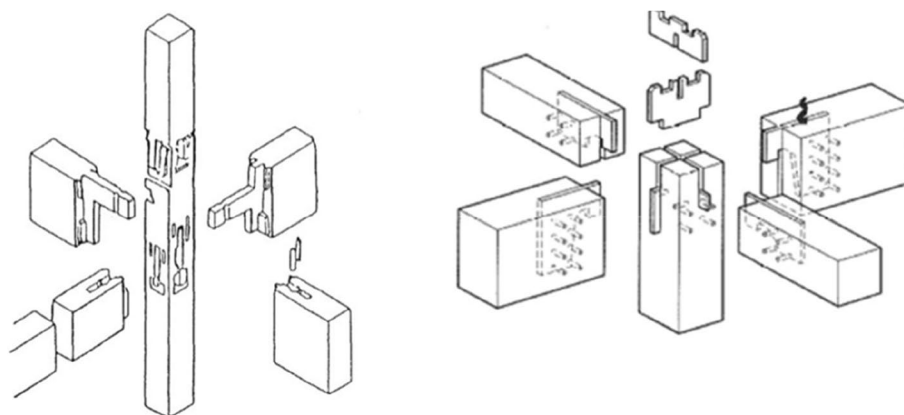


Fig. 6 Traditional Japanese Framing Joints (Graubner, 2002) (left)—Janebo system (Schwaner, 1997) (right)

in each joint system. In addition, they all suffer from local damaging of timber when driven to ultimate limit state.

For each joint system, this review showed common limitation for their applicability, load-bearing capacities, manufacture and discussed disassembly-and-reuse potential. Industrial metal sheet connectors revealed more sensitive and are eliminated because of their low potential in terms of reuse/sustainability.

Rod-types assembly present obvious qualities while reusability is not their strongest point. Our analysis pointed out the advantage of contact joint and the specific meaning of notch joints in the framework of digital fabrications of joints in timber.

2 Theoretical framework

2.1 Theory of plasticity and lower bound theorem

The theory of plasticity brings an answer to the inconsistencies of elastic theory, considering the ductility of the material and its consequences on the redistribution of stresses (Baker, 1956).

Both static and kinematic theorems of plastic design were first theorized in 1936 by Gvosdev and Feinberg, which Greenberg and Prager proved in 1949. The lower bound theorem, particularly suited for design purposes, says: for an ideal plastic material, any limiting load obtained from a distribution of internal forces is less than or equal to the actual limiting load.

As a result, designing a possible structurally working solution is sufficient to guarantee the safety of a structure if built with ductile material. Hence, a graphic statics drawing is one possible solution to the static theorem; equilibrium-based design was born, allowing for the management of different materials, structural typologies, or scales, while respecting the three initial conditions of the plastic static theorem. Robert Maillart's work on

detailing his structures can be considered as an application of this theorem.

2.2 Plastic design and STM approaches

Thanks to the lower-bound theorem of plasticity, any continuous structural system made of a plastic material can be modelled as a strut-and-tie network. The strut-and-tie modelling (STM) approaches were developed for the analysis of shear-walls and structural details in concrete structures based on plastic theorems.

Modelling the structural behaviour of complex structures by strut-and-tie networks is a common practice in structural engineering when Bernoulli hypothesis does not apply, which has been effectively evidenced by several contemporary structural engineers.

Strut-and-tie models are considered by (Fivet (2013) as high-level structural abstractions that depict the force path acting inside a structure in the most reduced way. It is composed only of rods in compression – struts – or in traction – ties – linking together pin-jointed nodes on which point loads can be applied. They can be used as generic abstractions inside a joint and for many types of structures such as pin-jointed frameworks or beams and frames subjected to bending moments, but also to trace lines of thrust in compression-only structures.

2.3 Characterization and applicability of STM for timber

Plastic principles are used for structural dimensioning of timber in most structural standards. Stress–strain relationship of timber demonstrates clearly plastic capacities in compression, both parallel and perpendicular to fibres. In contrast, timber is fragile against traction forces, particularly perpendicular to fibres, with a resistance below one twentieth of the tensile strength along fibres. In most structures, the required ductility for using the principles of plastic analysis and design is reached through the

plastic capacities of timber in compression and the ductility brought by steel components of joints.

Due to limited properties to redistribute force in tension, timber should be given special attention for contact joints alone, when modelling it using struts and ties, to avoid possible brittle failure due to tension forces.

In this regard CLT panels, which are composed of several interlocking layers (three, five, seven or nine) of planks placed side by side are of interest. These changes in direction within the material provides stiffness and resistance that are comparable in both main directions of the plane and enable using the principles of Strut-and-Tie Modelling in the framework of plastic design.

3 Timber-to-Timber design using STM

3.1 Classical notch joints for digital design

In the scope of steel-free joints, traditional eastern joints are mainly right-angle assemblies between post and beam construction acting with bending forces against horizontal loading. On the contrary, western structures use diagonal bracing to manage horizontal forces and enhance the range of load-bearing capacities. As suggested above, timber-to-timber joints (i.e. notch joints) open a wide field of applications for digital fabrication and circular use of timber-based material. Their simplicity in geometry enables their manufacturing means. Because the angle and the position of the saw or mill compared to the

timber element can be digitally determined, it can reduce the manufacturing time and increase the precision.

A widely used joint in traditional carpentry is the front notch joint. It transfers roof load (N in Fig. 7) through the rafter (diagonal member) to the support N_v and the tie beams N_h (horizontal member).

3.2 Joint dimensioning using algebraic tools

Based on a simple algebraical analysis and two dimensioning criterion equations (local resistance of timber in the notch and shear resistance of the heel), the behaviour of notch joint is quite well controlled as far as some basic hypotheses are fulfilled:

- forces trajectories are converging as for truss bars;
- the forces applied to the system are limited to those following the line of the two assembled bars, so that usual analytical methods may apply;
- the angle between the inclined compressed member and the connected element is between 30 and 60°, so that the assumption of a direct transfer only through the sole contact front area of the joint may apply.

Their full analysis involves several equations which allow the different failure modes to be checked: respective resistance in traction or compression of each member; local compression strength of timber at contact

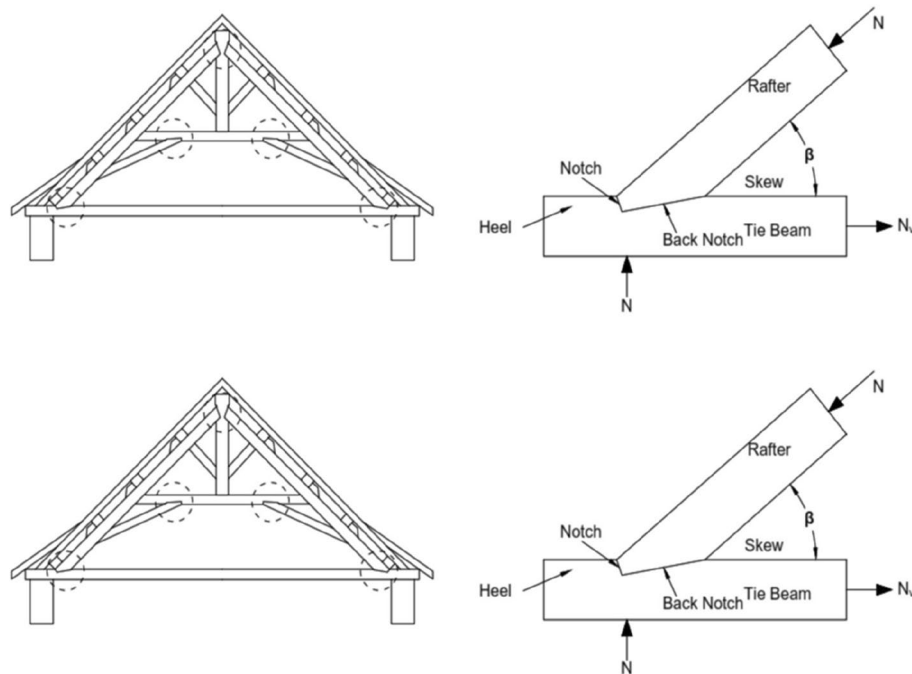


Fig. 7 Traditional carpentry with notch joints (circled) (left) – Single notch joint (right)

points according to the possible angles with wood grain; possible shear failure of the heel.

Outside the above-mentioned framework, these equations are not valid, showing that the commonly used algebraic method has its shortfalls for several cases.

However, by analysing the stress transfer in detail, it appears that a bending reaction is created from the notch on the heel involving traction in the heel (perpendicular to wood grain direction) with “e” being the lever of arm (see Fig. 8). This can explain the limitation of the skew angles imposed by the algebraic method, demonstrating the limits of this approach.

3.3 Addressing the problem through STM and stress fields

When analysing and controlling the behaviour of contact joints, a similar issue appears as for concrete cases. For concrete, truss analogy, and later strut-and-tie modelling enables to use modelling hypothesis leading to a proper dimensioning when sufficient ductile behaviour can be activated. The analysis is achieved on reticular systems of bars assembled by hinges: the STM model. When it comes to dimensioning, the complete version of STM including the required thickness of both strut and ties is known as Stress fields Theory. According to the proper theoretical set of hypotheses related to plastic design, thicknesses are provided to struts – which transverse dimensions correspond to required width of a uniform stress field – assembled by nodes supposed to

resist to composed-stress state. The dimensioning is then achieved by checking stress states in both members and nodes. A clever dimensioning with strut and ties may suppose that no shear will occur if stress fields follow main stresses directions, which simplifies the analysis. Nevertheless, in nodal stress fields, compound stresses need to be checked and local tension stresses may occur. If they are adequately situated in the thickness of structural members, these stresses can be resisted. This set of assumptions is the basis of structural analysis of timber joints using STM.

The model shown in Fig. 9 illustrates the application of STM within a single notch joint of a skew angle of 25°, considering the load transfer in the back notch,

The considered thickness of the struts must consider the anisotropic behaviour of timber and the STM must follow specific modelling hypothesis regarding the position of the nodes and the ties. To remain close to the elastic solution, the STM must then be optimised. This can be achieved by defining the strut and tie network that minimize the deformation energy. Reliable resistances values that are obtained are consistent with what is observed from lab tests.

Through an experimental campaign held in LEMSC (2024, Zastavni, Misson et Al., in preparation), the diagram in Fig. 10 has been recorded.

Computation with STM for this configuration gives results closer to the experiment results than algebraical

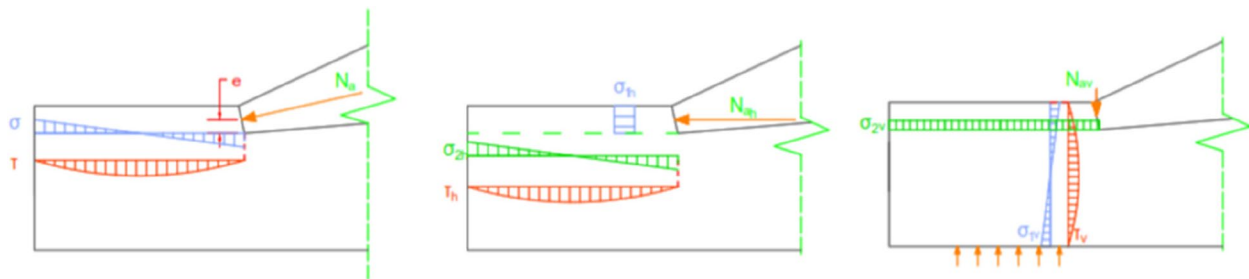


Fig. 8 Description of stresses and load in the tie beam

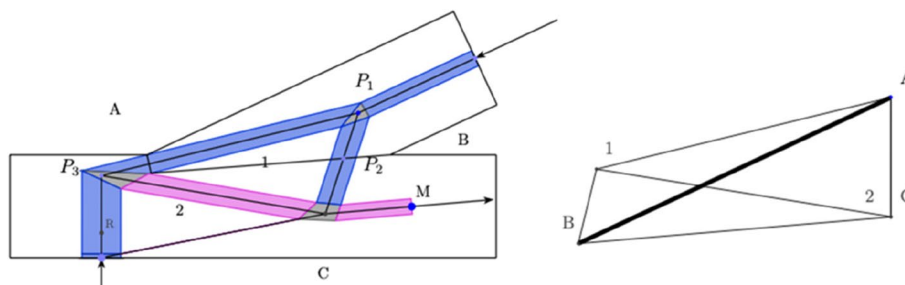


Fig. 9 STM for a single notch joint of 25° (left) and its corresponding force diagram (right)

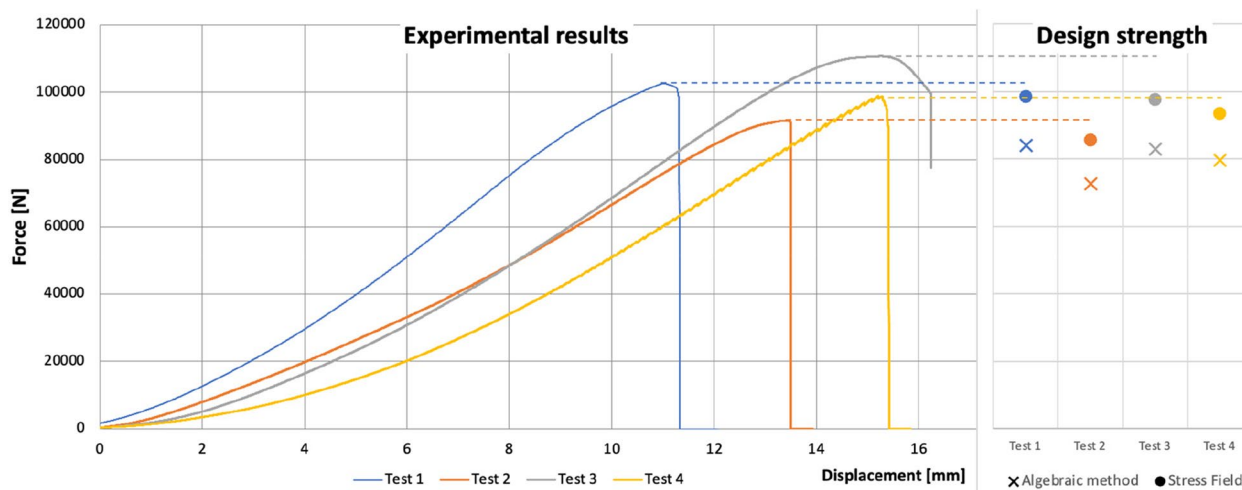


Fig. 10 Force/Displacement diagram for four single notch and their corresponding design strength from algebraic equations and stress field methodology—destructive tests realized during an experimental campaign held in LEMSC (2017)

computation, and for the specific case of the skew angle of 25°, it is too small than permitted by classical algebraic method.. Another experimental campaign with single notch of 40° gave an average resistance result that was closer to reality with the STM approach than with the algebraic approaches. The test-campaign also showed that the below-listed parameters may deeply influence the results and limit resistances:

- wood defect or angle deviation of wood grain considered in the computation,
- Parasitic forces in the supports,
- Poorly crafted joints.

Since ideal support and connection conditions do not exist in reality, sound design must take account of possible hazards in structural operation and should be an integral part of the designer’s approach.

3.4 Risks of fragile failure in contact joints

Following the principle of the lower bound theorem of plastic design, improperly defined strut-and-tie model, considering the actual structural behaviour, will lead the system to redistribute forces to another equilibrium state for this system of forces. Designing a strut-and tie model acting mainly in compression and connected to a central traction tie-beam seems to be an adequate strategy that will not lead to failure mechanism.

Two phenomena interfere with a free organisation of forces: the first is that according to the angle made to wood grain, material stiffness will vary, encouraging some directions for forces trajectory instead of another. A second phenomenon is the possible discontinuity in the

mass of material. This can disturb the simple interpretation in terms of compression and tension stresses only. For examples, cracks or split in timber due to shrinkages, or open breaks at the edges of planks in composed sections can lead to specific shear forces in weakened sections along discontinuities.

Depending on these parameters, the STM model can evolve towards systems implementing more tension trajectories that will reveal to be the weak point of the structure with little plastic capacity. As for concrete, STM and stress fields under the applications of the lower bound theorem can be developed without damages if the devised plastic solution is close to the actual solution. If resistance boundaries of the system are not reached, this solution correspond to the (actual) elastic solution. Solutions developed in nature and minimal shapes can be reached by several numeric approaches based on minimizing strain energy. After, STM model provide reliable candidate solutions that reveals thrustable. The classical approach followed School of Stuttgart for delivering meaningful STM in concrete was indeed to follow the line of an analysis using FEM or analytical analyses to characterize elastic stress fields on which the strut-and-tie model was built. An approach based on minimizing strain energy turns STM possible and reliable to design stress fields in timber joints.

As an alternative, there are material conditions that offer possible solutions while not fulfilling the plastic requirement for a minimal solution. In concrete STM, required a certain ductility that enables the redistribution of forces without damage. This can be provided through concrete grades with a sufficient plastic behaviour and steel reinforcement (ductile) for tension forces.

Self-tapping screw or glued-in rods appropriately disposed in possible tension zones offer sufficient ductility that enable brittle failures to be avoided. Although self-tapping screws are reversible and cause tolerable local damage (or can be held in place when structural elements are reused), and optimised STM work for efficiency and reliability can still be sought for these reasons.

3.5 Integrated universal approach

As a conclusion, using STM modelling with shape or topological optimisation to achieve geometric arrangements fitting the elastic solution enables Stress Fields Theory to be applied to timber joints. Vector-based 3D Graphic Static demonstrated useful to devise structural arrangements acting mainly without bending, such as pin-jointed networks constituted of elements in traction or compression. This is very appropriate to design STM. The complementary use of the interactive vector-based tools both at the scales of the global structure and the details/connections provides a comprehensive and unified environment to design timber structures with specifically defined efficiency goals. Among them, digital fabrication of timber structures and guaranteeing sustainability through their reuse with easy disassembly-reassembly can be achieved through bars systems engineered with the VGS tool (Jasienski 2023).

4 Research by design – a case study

4.1 Research by design

An in-depth study integrating the multiple parameters introduced previously (see 1.1) benefits from being based on a research-by-design-type approach, where prototyping can have an important role to play. The final solution is neither necessarily defined nor known. Typically, research-by-design can be implemented involving masterclasses, workshops, and project development for

architectural competition. This method has the capacity to reveal structural approaches or limitations about complex design issues (Fig. 11).

The case study presented in this chapter is the project of the extension of a renown international centre of excellence for musical training. The teaching is reserved for highly skilled musicians. At the time of its creation, the famous critic Vuillermoz already described it as a kind of ‘modern Villa Medici’. The 3d year bachelor engineering architectural students involved in the exercise are asked to design, in the vicinity of the existing buildings, a medium-sized rehearsal and concert hall and three to four pavilions for hosting artists in residence (all in timber structure).

4.2 Research objectives

The structure of the main hall must be integrated into the design process from the beginning by groups of students in the framework of research-by-design. Assignments are to design the project and develop the timber structure. The brief of the task can be summarized as follow:

- design the structure to support vertical forces – dead loads, live loads -, horizontal forces – wind – in X and Y directions;
- model the structural behaviour with the aid of strut-and-tie modelling;
- build this model in the Rhino and Grasshopper (McNeel 2023), environment and analyse it with the VGS-tool (Jasienski 2023); detail a specific joint of the structure, assuming the sections are cut to transmit maximum forces through direct contact, while avoiding the use of steel fasteners. The joint is designed to make it possible to transfer forces according to their nature (tension/compression): contact planes, possible anchoring of tensile forces,



Fig. 11 View of the work of group 02: model of the concert hall

possible assembly of the joint, restoration of continuity of one or more bars, etc. The purpose is to promote the direct transmission of forces between timber elements, in the direction of the fibres. The cuts for the assembly can be made using digital fabrication (such as milling) and thus can have complex geometries.

Regarding the computation hypothesis, students were asked to do a simple calculation in admissible stresses, without any increasing factor on the loads. They considered only a safety factor on the admissible stress of the materials.

4.3 Results

The design and development of the structure progress together through drawings, assessments, and models (see Fig. 12). Various support systems are studied to sustain roofs and facades while withstanding snow and wind loads. The large span is dimensioned based on the necessary capacity and architectural constraints. All or part of the structure is modelled using struts and ties in the parametric environment of Rhino and Grasshopper (McNeel 2023), allowing for continuous adaptation of the structure.

Here, designers ensure the static equilibrium of their structure by using form-finding tools such as

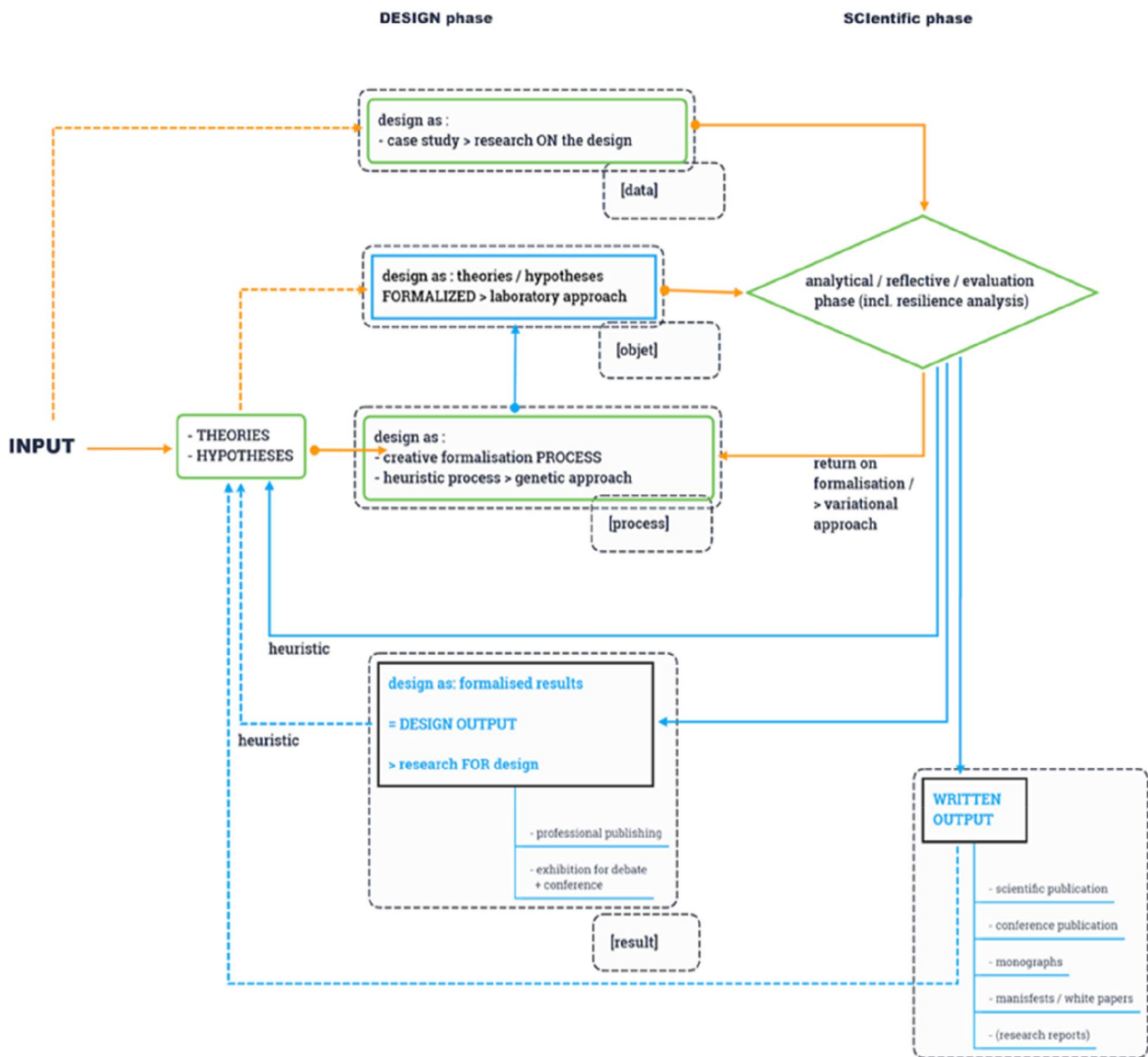


Fig. 12 Research by design main significances [credits Denis Zastavni and Commission RPP, 2021]3.2 Research context – design task

Combinatorial Equilibrium Modeling (CEM – Ohlbrock and D’acunto, 2020) or others approaches. The structure is analysed using the VGS-tool (Jasienski 2023), with its transformation module to refine the structure according to the goals defined by groups of two, such as minimal forces, minimal sections, required height, specific acoustic shape, or zenithal openings, etc. This process of analysis and optimisation converges towards the definition of the shape and efforts of the structure. These assumptions are then used to design a joint to be manufactured using digital fabrication (see Fig.13).

The diversity of structural models reflects the variety of approaches proposed by the students in defining at the same time the architectural and structural project. A few groups managed the exercise with three-dimensional strut-and-tie modelling. With the help of CEM (Ohlbrock and D’acunto, 2020), they were able to achieve a balanced structure despite the complex geometries (See Fig. 14).

The VGS-tool allowed for a comparative analysis of the values of forces in the bars of the STM models. This can be done node by node using the vector-based approach of VGS: “Regarding the strut-and-tie network as a form diagram F , the equilibrium of the inner forces

within the structure can then be solved iteratively node-by-node using vector-based 3D graphic statics”.

Based on the proposed graphic statics diagrams, timber joints can be designed according to applied forces (see Fig. 15). A critical examination of students’ assemblies quickly revealed numerous pitfalls, such as managing different loading cases, inadequate bearing surfaces, insufficiently balanced forces, use of metal fasteners for ductile failure in tension, excessively weakened sections due to notches or facet orientations in relation to the forces, ... This revealed the complexity of such an exercise.

Generally, the designed assemblies involve mechanisms that quickly lead to failure. For example, in the case of the support of the beam of group 04 (see Fig. 16): if a moment caused the beam to rotate around its support, the tie and the column in tension could cause brittle failure. Conversely, the tie in tension and compression in the column would pull the tie out of the column and cause failure as well.

These examples highlight the benefits of a rigorous methodology to design timber-to-timber contact assemblies, with the advantage of using three-dimensional structural models designed and analysed by the VGS tool.

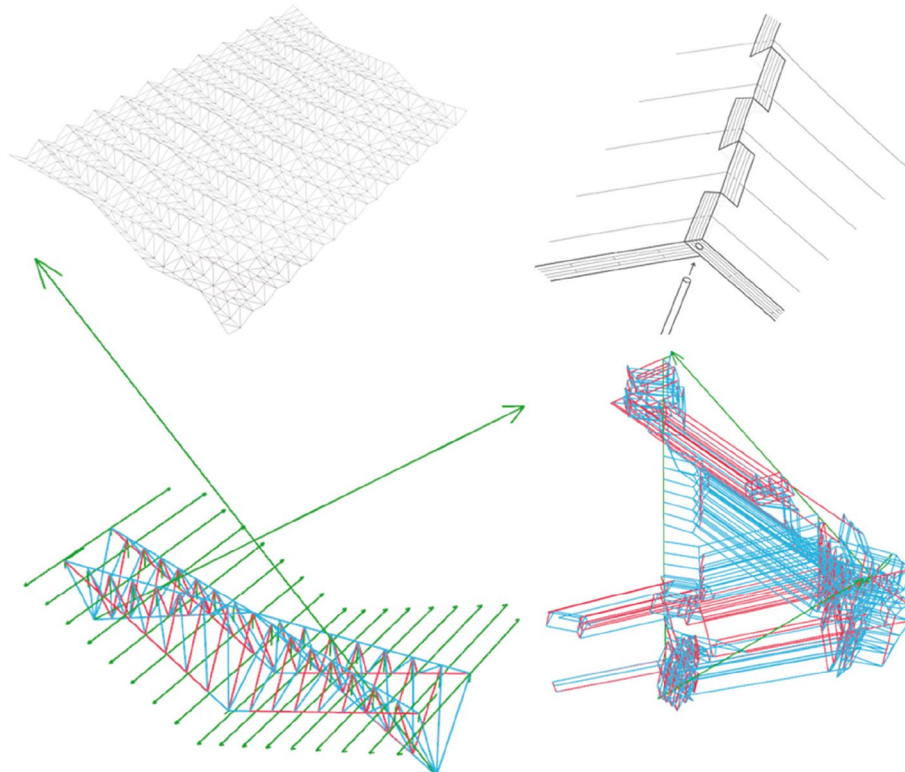


Fig. 13 Synoptic results for a design – from top left to bottom right: structural model of the proposed roof made of CLT (Cross Laminated Panels), assembly drawing trial for a joint system of two CLT panels with a blocking dowel, form diagram with support forces acting on neighbouring panels, force diagram with external forces (green) forces in compression (blue) and tension (red)

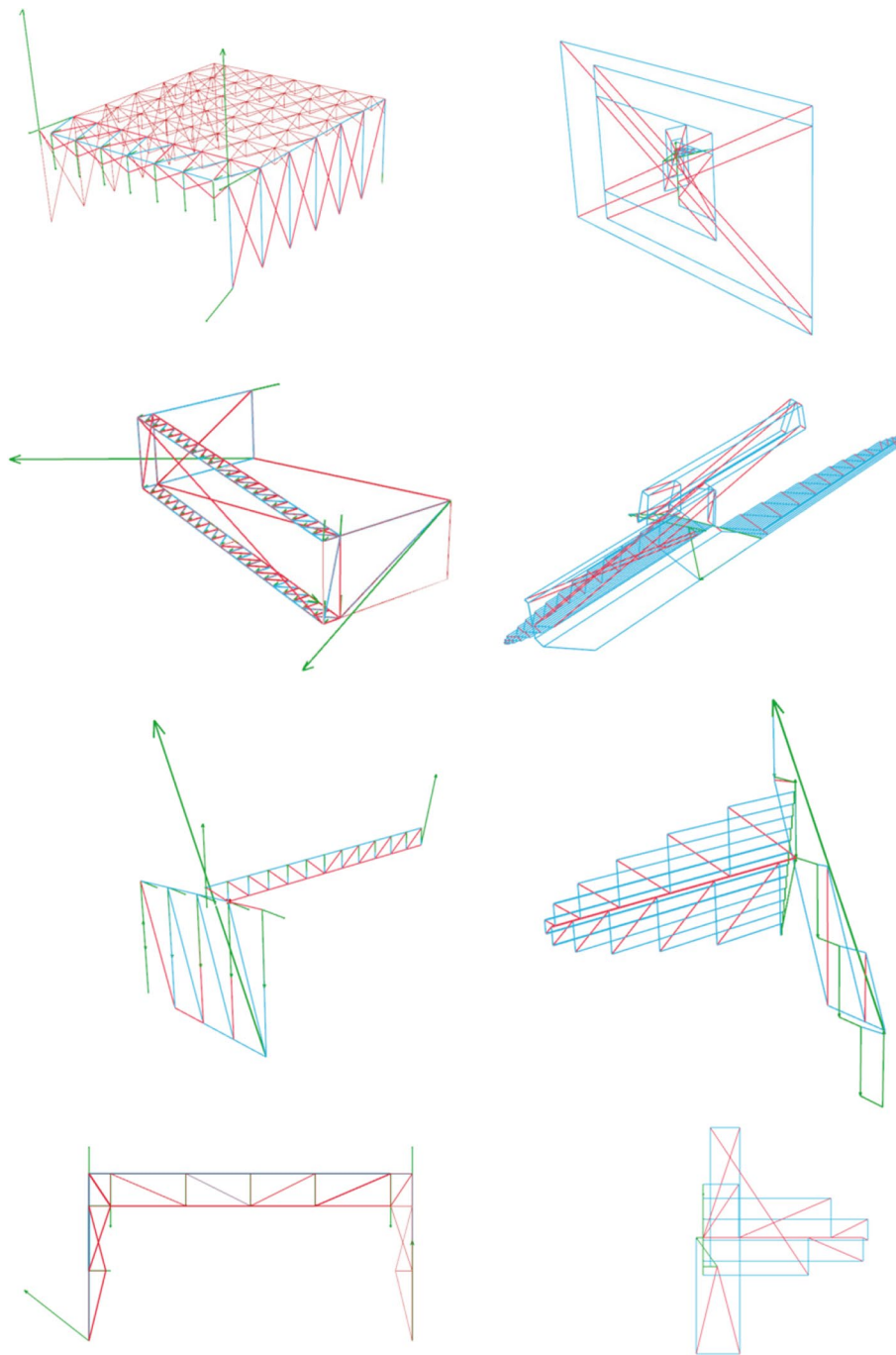


Fig. 14 Form diagram (left) and forces diagram (right) of the primary structure, each line represents a project. First line: full structure of the concert hall with members in compression (blue), in tension (red), support forces (green) and corresponding force diagram on the right. Second line: three-dimensional part of the stiffener portal frame of the concert hall. Third line: detail of the support of a beam on a wall, the whole modelled by a wooden frame. Fourth line: two-dimensional portal frame with the members visualized according to the acting forces

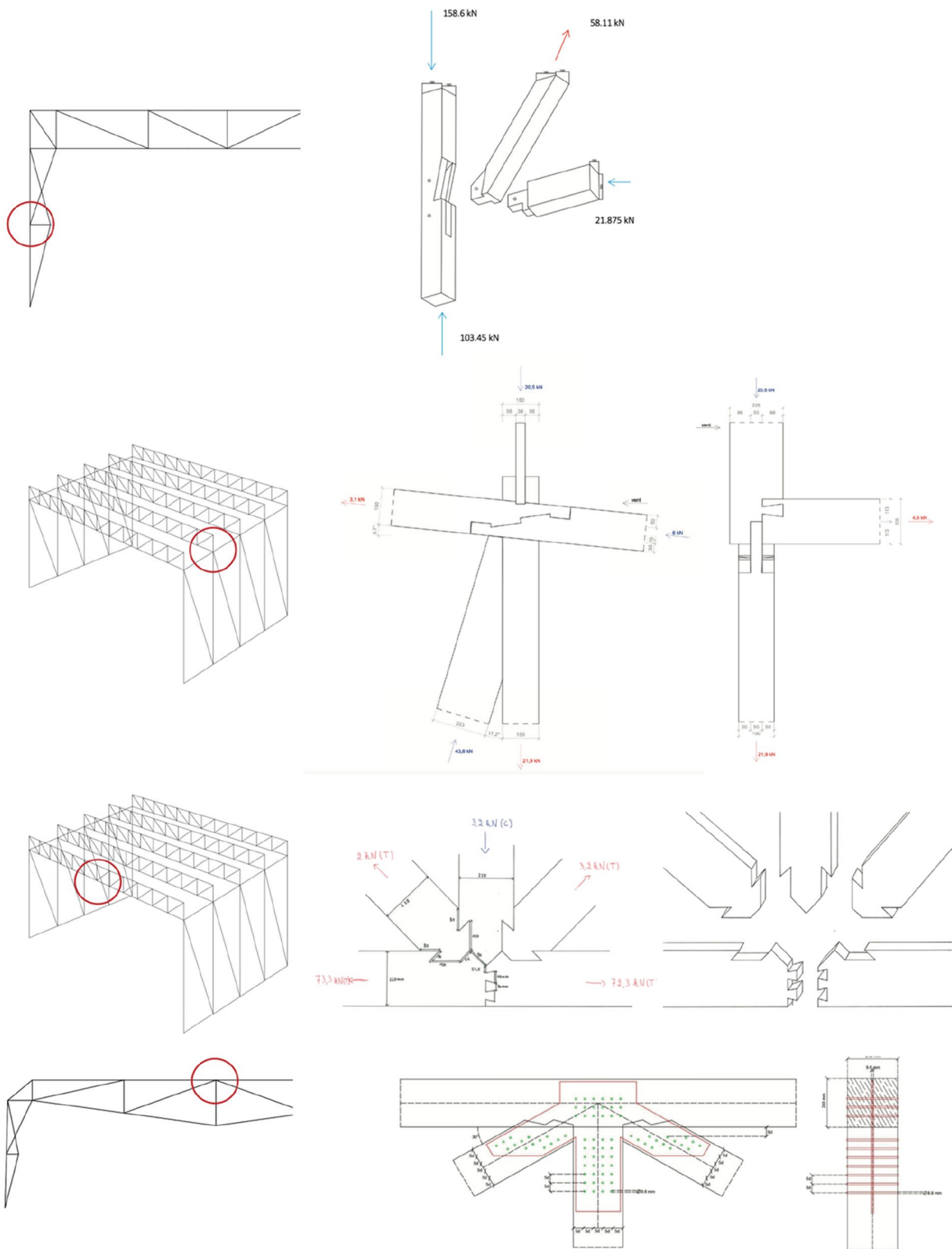


Fig. 15 Structural model (left) and proposed attempt for a timber-to-timber joints (right). Each line represents a project. First line: part of the concerned portal frame, detail of the wooden assembly with acting forces deduced from force diagram on Fig. 14. Second line: detailed connection of the support of a beam on a wall with wooden assembly cuts. Third line: detailed connection of 5 members in compression and tension. Fourth line: detailed connection of 5 members in traction and compression with steel assembly plates

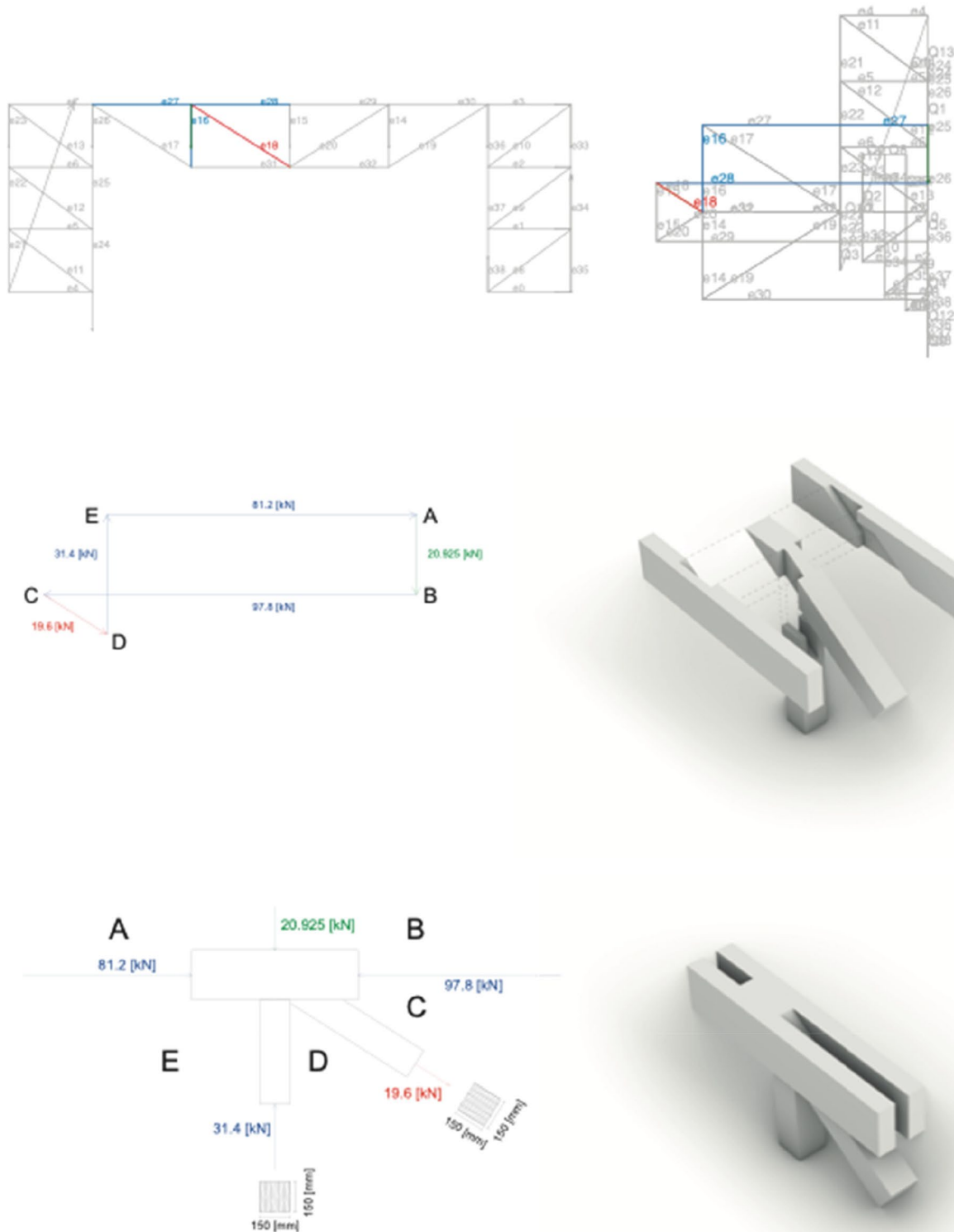


Fig. 16 First line: form and force diagram with highlighted members of the detailed connection (left) and corresponding acting forces (right). Second line: force diagram (left) with detailed external force (green) compression forces (blue) and tension forces (red) and exploded axonometric view of the assembly. Third line: form diagram with all acting forces (left) and closed assembly (right)

5 Discussions and future work

The research article proposed a workflow for the design of timber joints and structurally efficient timber structures using Vector-based Graphic Statics. In the context of structure designing that need to comply to an increasing set of criteria, this methodology reveals to provide a reliable design at early design stage. Furthermore, the VGS tool relies on the force and the form diagrams and their visualisation enable an intuitive analysis between the geometry of a structure and their inner forces.

From a historical perspective, an efficiency analysis on sustainability and potential robotic fabrication, the choice was made to investigate timber-to-timber joints. The lower-bound theorem of plasticity enables to model a load transfer within a material through a strut-and-tie network. Given that wood has a fragile behaviour in traction, especially perpendicular to the fibre, the theorem is only applicable for timber in a network where the dominant mechanism act in compression. The application of strut-and-tie model and the stress field theory within a computer-driven framework for the energetic optimisation of the network provide an intuitive timber joint design. Following a serie of lab tests on single notch joint, the presented approach reveals to give more accurate results than the traditional algebraic methodology.

For timber structure, the VGS methodology was applied to a research-by-design consisting of a multi-factorial design task for students of 3rd year Engineer Architect. Even if they could not fulfil all the initial objectives simultaneously, resulting designs demonstrate the interest of the proposed workflow. Because of the complexity to visually represent these complex connections and the forces involved, a node-by-node approach, with superimposing form and force diagrams, is not always sufficient for a full understanding of the way assemblies' work. In future design sessions, using a representation of contact surfaces will allow to go beyond intuition and provide a better control of stress trajectories and failure mechanisms. More globally, at the scale of the whole structure's design, enabling interactive informed structural assessment allows for the eye's intelligence to activate brain-driven optimised design process – this becoming hybrid approach when computer is involved in optimisation. The parametric nature of the VGS approach in a multi-factorial design project workflow demonstrated its interest for tackling timber design challenges. Based on an adequate representation of connections and an iterative use of VGS, future design sessions are to allow a more precise development of timber-to-timber connections to support a sustainable evolution of timber structures.

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Authors' contributions

Sylvain Rasneur oversaw the technical course supporting the students' modelization of their projects developed in the design studio as structural models in VGS. As a main author and researcher in structures and technologies, he specifically contributed to the sections related to the context, the design of timber structures, the theory of plasticity, strut-and-tie models, and the research-by-design part. His contribution is thus present in all the sections of the paper.

Prof. Denis Zastavni contributed to the full content of the article. He is an expert in graphic statics and oversaw the design studio from where the results are presented in Sect. 3. He was also supervising the tests done in the LEMSC in 2017 by Jean-Charles Misson which constitute the core of Sect. 2. He is also an expert in timber construction and provided important knowledge for the part about the joints and assemblies. His contributions are present in all the sections of the paper.

Jean-Charles Misson contributed specifically to Sects. 2.4 to 2.7. He carried a series of tests in the LEMSC in 2017 to compare the result of STM approach to timber joint to real tests.

Jean-Philippe Jasienski is a specialist in 3D vector-based graphic statics and one of the developers of the VGS-tool. He was assisting prof Zastavni for the design studio from where the results are presented in Sect. 3 (research-by-design). He contributed mainly to Sects. 1, 3 and 4.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

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Consent for publication

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Competing interests

The author(s) declare(s) that they have no competing interests.

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