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EFFECT OF DESIGN CONFIGURATION ON GLOBAL STIFFNESS OF VOLUMETRIC TIMBER MODULES

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ABSTRACT: Due to the environmental advantages of wood as a construction material and the distinct benefits of modular construction in terms of time savings, modular timber buildings have recently gained interest in academia and industry. Additionally, volumetric modules are promising in terms of their potential for reuse. Currently, industry is challenged with ensuring the structural capability of volumetric modules while simultaneously fulfilling the criteria for creating large openings for facades and windows. Therefore, this study examines the impact of design configurations on the structural performance of volumetric timber modules to enhance their application in buildings, utilising practical data from the Danish building industry. Numerical analyses of the volumetric product are carried out using a high-fidelity model, including the fasteners, to determine the response to different external loads. The initial model is subjected to various design configurations to investigate their impact on the overall stiffness of the volumetric module. The discussion will serve as a reference for improving volumetric timber module design throughout the industry.

KEYWORDS: volumetric timber module, mechanical connections, structural rigidity, numerical analysis.

1 – INTRODUCTION

Future construction projects should be designed to minimise carbon emissions in response to anthropogenic climate change. A recent life-cycle assessment (LCA) of high-rise buildings showed that replacing steel and concrete with wood can lower carbon emissions by 25% [1]. With developments in engineered wood products, timber buildings are no longer limited to low-rise structures [2, 3]. The construction of modular, lightweight timber frame buildings has gained popularity, offering enhanced safety and efficiency in the building process. This study addresses the engineering challenges of timber frame modules in the Danish construction industry. Based on interviews with Danish producers, the construction method follows standard practices for traditional timber frame houses, and the design is based on the Danish standard for timber frames, which has not been adapted for modules. Current calculations are analysed based on individual panels instead of an entire modular component. The interviewed engineers highlighted challenges in the contemporary design trends, such as the installation of wide and tall windows in facades, which reduces the structural load-bearing capability of the walls [4].

While timber structural systems have been an increasingly prevalent research topic, the literature is limited in the study of the structural engineering aspects of spatial timber modules. Miedzialowski et al. [5] and Ormarsson et al. [6] addressed the structural design of timber frame

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modules based on numerical and experimental analyses of multistorey buildings. They concluded that the global stiffness of the modules is greatly influenced by the opening configuration and connector stiffness. Also, the behaviour of the buildings is significantly influenced by the connections between modules, the arrangement of load-bearing walls, and the configuration of window and door openings [7]. Few researchers focus on parametric modelling and analysis of timber-framed volumetric modules [8] and modular building structures [9].

The purpose of this study is to conduct a comprehensive numerical analysis of a spatial timber frame module to comprehend how it responds to various load conditions and the effect of different configurations, including variations in panel configuration and opening placements.

2 – METHODOLOGY

To investigate the influence of various parameters on the overall structural behaviour, it was essential to first specify the volumetric module for evaluation. The parameterized module is built via Python scripting using ABAQUS [10] as a modelling platform. For the comparative analysis, a basic module will serve as a benchmark configuration. The model is subjected to various load combinations. Afterwards, different configurations are examined, including openings and facade variations, to determine the effect on the stiffness of the module.

2.1 Volumetric timber frame module

This study concerns a module with a ceiling height of 3.14 metres, a width of 3.265 metres, and a length of 4.245 metres. This is informed by the findings of Li et al. [11] regarding the average dimensions of volumetric wood modules. Sheathing was applied to both sides of the studs on load-bearing walls and facade walls. The horizontal ceilings and floor panels comprised sheathing panels and Masonite beams [12]. A Masonite beam is an I-beam composed of two flanges and a web that are glued

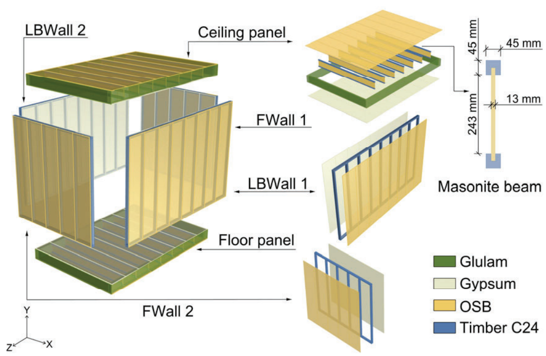

Figure 1. Volumetric timber frame module.

together with adhesives. Fig. 1 illustrates the composition of the fundamental model and the selected materials.

Table 1: Cross-section of the components in a timber frame panel.

	Cross-section [mm × mm]			
	Load-bearing wall	***Facade wall***	***Floor panel***	***Ceiling panel***
Studs	45 × 95	45 × 95	45 × 333	45 × 333
Frame plate	45 × 95	45 × 95	110 × 333	110 × 333
Sheathing panel	15 × 600	15 × 600	15 × 600	15 × 600

The selection of cross sections and materials for all components in the timber-framed panels was mostly derived from an interview with BM Byggeindustri (a Danish timber module manufacturer) and Lilleheden A/S's catalogue, the handbook of Saint-Gobain Sweden AB, and the research conducted by Kuai et al. [13, 14, 15]. All fasteners in the model have a diameter of 3.9 mm, with the stiffness set at 10^7 N/m [4]. The design parameters for cross sections are presented in Table 1.

2.2 Finite element model

The finite element model utilised in this study is based on the theory of continuum mechanics. The main structural components were modelled in high fidelity using solid elements. The accuracy and global behaviour of the FEM model depend significantly on the type of solid elements used. To prevent shear-locking and spurious modes, 20-node hexahedral elements with reduced integration and hourglass control were employed, and the mesh size was set to 0.025 m to achieve accurate results.

Steel angle brackets were included in the corners of the load-bearing wall panels, connecting the studs to the bottom and top plates. Furthermore, mesh-independent fasteners were employed to mimic mechanical connections between the studs and the plates constituting each wall panel. The same method was used to simulate the nails, screws, and staples coupling the joists and the plates constituting the floor and ceiling panels. This provides a low computational cost without compromising the accuracy significantly. A comparison with an approach, where the plates were tied to the joists and studs (this resembling glued connections), showed that it is important to model the mechanical connection even if the method is a simplification.

The study aimed to investigate how the loads transferred from an upper floor module will impact the structural behaviour of the considered module. As show in Fig. 2, the loads and supports were placed at the inter-module connection points, which were assumed to be aligned

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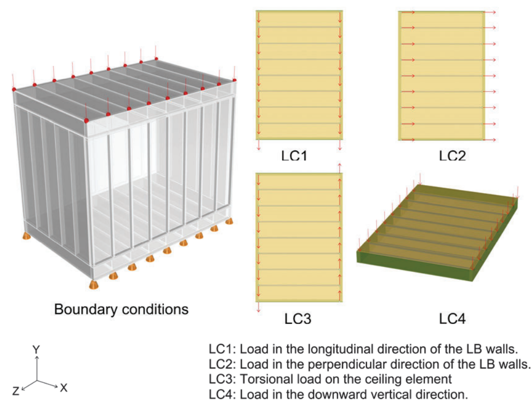

Figure 2. Boundary and load conditions.

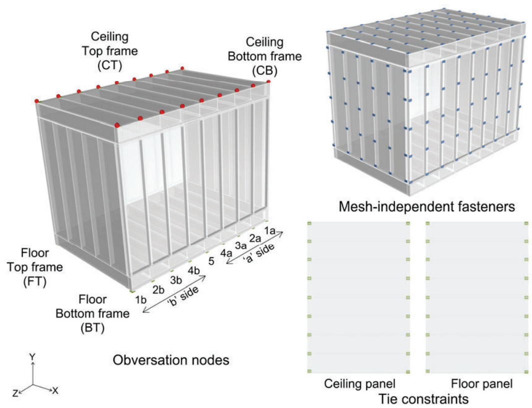

Figure 3. Named observation nodes and interaction settings.

with the studs in the load-bearing walls. Shell elements were embedded within the ceiling and floor panels at the inter-module connection points and coupled to the solid parts by tie constraints. Thus, the forces were distributed over an area corresponding to the cross-sectional area of the studs, allowing the introduction of supports and loads in single nodes without excessive local deformation.

Four fundamental load cases were identified as important for the structural behaviour of the module: 1) horizontal load applied longitudinally to the load-bearing walls, 2) horizontal load applied perpendicularly to the load-bearing walls, 3) torsion of the ceiling panel, and 4) downward vertical load. These load conditions are based on real-life scenarios, such as the vertical load from gravity or the horizontal loads from wind acting on the modules above. The different load cases are shown in Fig. 2, and in the present analyses a magnitude of 0.3 kN was applied for each point force. Further, as boundary conditions, simple supports were applied in all analyses. This should be kept in mind when studying the results.

Two different parameters were used for the assessment: the displacements at selected observation nodes and the stress distribution across the module. The displacement was extracted to evaluate the stiffness of the module on a macro scale, whereas the stress distribution was utilised to understand which parts of the module are more exploited in each considered load case. Although it has not been done in the present work, it should be noted that the macro-scale stiffness can be used for the assembly and subsequent static analysis of a building model with several modules connected via the shell-reinforced nodes, while the extreme stresses can be used to assess the capacity in the ultimate limit state.

In Fig. 3, the observation nodes used for the extraction of displacements are marked in red. The same nodes were utilized for applying loads and observing displacements. As indicated in the figure, the observation nodes are named CT, CB, FT, and FB, along with a numbering, where C and F indicate if the nodes are placed in the ceiling or floor panel. The tie constraints used for coupling the shells to the solid parts at the inter-module connection points are marked in green, while the mesh-independent fasteners are marked in blue.

2.3 Parametric modelling

A functional program was developed for generating intricate hierarchical structures parametrically, allowing the simple definition and modification of the model in a reproducible manner. The parametric model was developed for the ABAQUS modelling platform using Python scripting. The computational method of this study is a continuation of the method developed by Anne Kristine Bak [16] for the parametric FE modelling of a timber frame wall panel, extended to generate an entire volume module, as the assembly of several panels. The program consists of five parts: *MainScript*, *PartCreation*, *PanelCreation*, *AssembleModule*, and *Interactions*, containing functions and settings for constructing the panels and the module. The parameter settings are stored in dictionaries by categories, such as general information about the assembly and program flow, settings for the timber framing, dimensions of the module, material selection, connector selection, mesh settings, opening settings, material properties, and loads.

2.4 Configurations

The parametric study aims to elucidate how different parameters influence the structural behaviour of a module in each considered load case. The benchmark configuration [*Benchmark*] has a fully enclosed facade,

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fastened to the loadbearing walls, and without openings in the loadbearing, longitudinal walls.

Firstly, to quantify the contribution of the facade walls to the module's overall stiffness, three alternative configurations were analysed. In *Facade_1*, the facade is only connected to the ceiling and floor panels. In *Facade_2*, the facade walls are completely removed, while in *Facade_3*, the facade wall has a width of 1.2 m. In each case, the facade panels are symmetric along the short axis of the module.

Secondly, three different opening configurations are explored. In [*Open_1*], the openings are placed 1.8 m from FWall1 in both LBWall1 and LBWall2. In [*Open_2*], the openings are positioned 1.2 m from FWall1. Conversely, in [*Open_3*], the opening in LBWall1 is located 1.2 m from FWall1, and the opening in LBWall2 is positioned 2.4 m from FWall1. The openings in this study represent doors with a width of 1.2 m and a height of 2.44 m, positioned 0.3 m from the top of the floor panel.

3 – RESULTS

3.1 Benchmark configuration

Fig. 4 shows the maximum absolute principal stresses (tension is positive and compression is negative) and displacements in the benchmark configuration for each of load case. It is noted that stresses in the grain direction and the transverse directions should be examined to assesses the capacity of the orthotropic materials.

In the first load case [*LC1*], the longitudinal load applied to the ceiling induces an uplift of the 'a' side of the module in the y-direction. The longitudinal walls have a more varied stress distribution than the facade walls.

In the second case [*LC2*], the forces applied to the ceiling act in the transverse horizontal direction. In the load-bearing walls, the larger stresses are present near the corners of the module. In addition, it is observed that large-magnitude stresses develop in the endplates within the ceiling and floor panels.

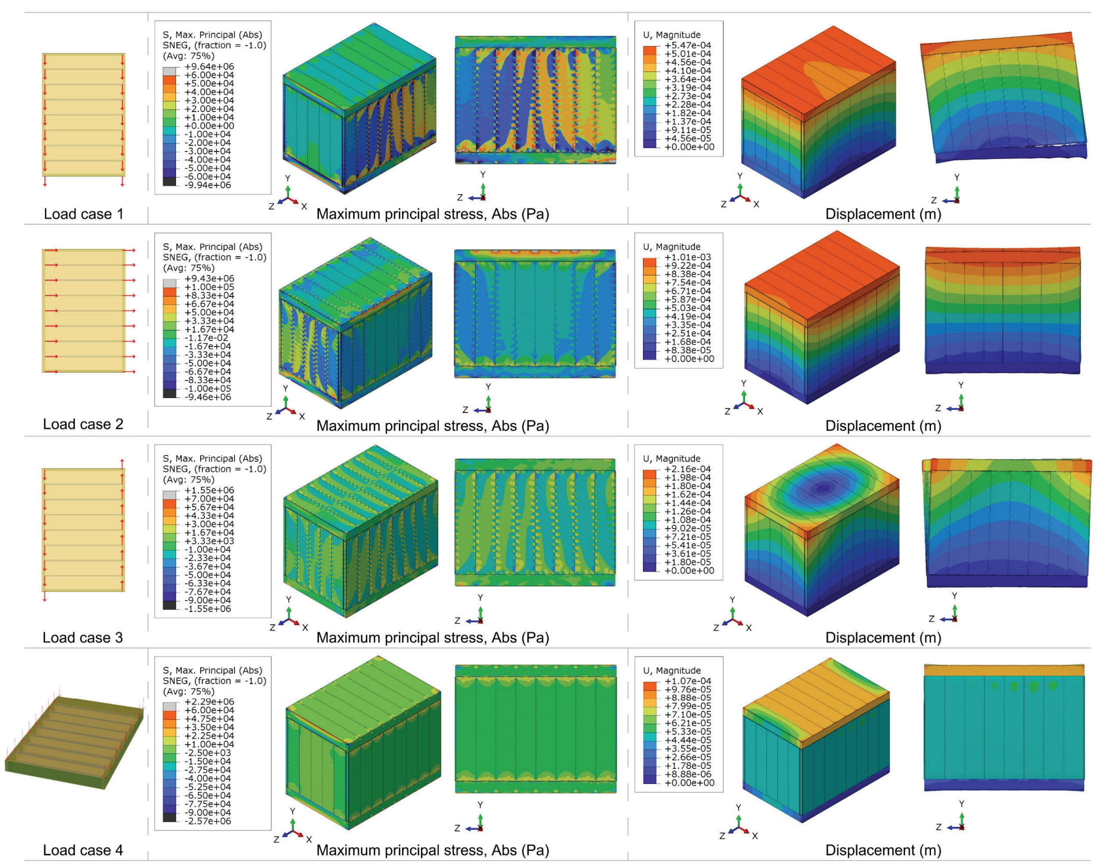

Figure 4. Stress and deflection diagrams, perspective and side views of the base module (from left to right), subjected to each of the load cases LC1, LC2, LC3, LC4 (from top to bottom).

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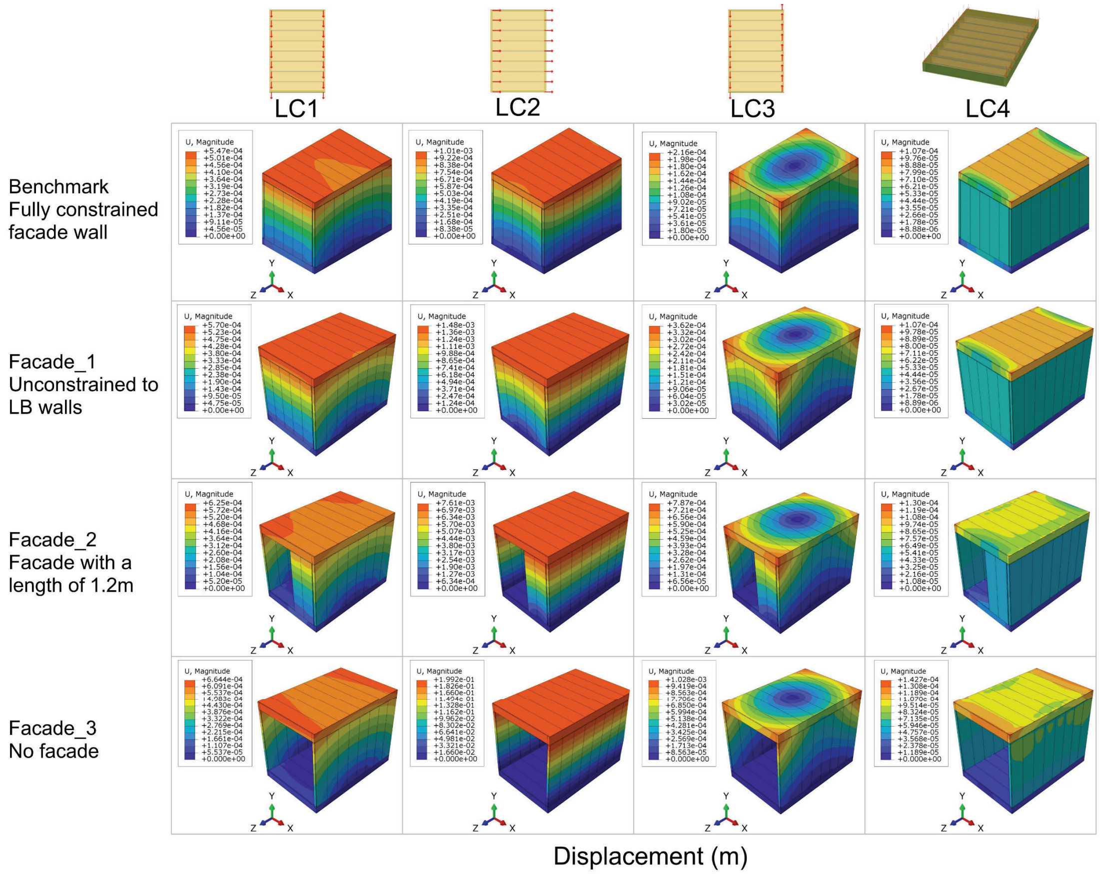

Figure 5. Diagram of deflections comparing the facade variations with the benchmark for each load cases (LC1, LC2, LC3, LC4, from left to right).

In the torsional load case [*LC3*], a twisting moment about the vertical axis is applied at the ceiling and transmitted to the walls through the fasteners. The deflections seen in Fig. 4 demonstrate a discontinuity at the corners, and the ceiling is observed to rotate almost as a rigid box.

The vertical load case [*LC4*] generates compression within all the walls but mainly in the longitudinal wall panels supporting the ceiling joists. In the first three instances, the stresses alternate between tension and compression in each bay between the studs.

3.2 Facade variations

This section presents the results of the fundamental load cases applied to modules with different configurations of the facade. The study includes a configuration with all walls present but no direct connections between the facade walls and the longitudinal walls in the corners. Two other configurations are considered, namely partially maintained facades and no facades at all.

The three alternative facade configurations are compared with the benchmark configuration. Due to space limitations, only the displacement fields have been illustrated in Fig. 5, i.e. the stresses have not been shown. Clearly, the existence of a facade wall is essential for the load scenarios perpendicular to the load-bearing wall. The module without the facade wall has the highest displacement in load case [*LC2*]. The deflection is increased from 1 mm to 200 mm compared to the reference module. In load case [*LC2*], the maximum displacement value of the partial facade wall is seven times the benchmark value. Conversely, the value for the unconstrained facade wall scenario rose by only 47%. This is still a substantial increase, indicating a significant loss of stiffness when the walls are not connected.

In the model without facade walls at all, the second most significant load type is the torsional load, with the maximum displacement resulting from the torsion of the load-bearing wall being 4.7 times greater than the benchmark value. The minimum difference for the vertical load [*LC4*] was 1.3 times.

3.3 Loadbearing wall variations

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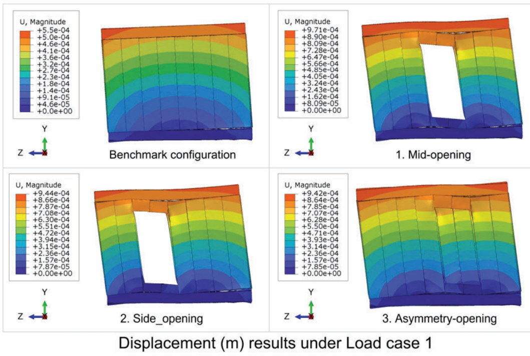

Figure 6. Comparing opening variation models deflection diagrams to the base module for LC1.

The opening results will be compared to the model under [*LC1*], which is orientated along the load-bearing wall where the opening is. According to the lateral displacement plots in Fig. 6, the opening has a significant impact on the magnitude of the deflection, indicating that its implementation resulted in the load-bearing wall rotating centred on the opening. The greatest difference occurs in module [*Open_1*] with an increase of 76%. In contrast, [*Open_2*] and [*Open_3*] had a 71% increase in deflection, suggesting that the stiffness of the module was not significantly influenced by the location of the opening.

4 – ANALYSIS

4.1 Facade variations

For consistency, a single deflection for every load case and module variation will be used when comparing the influence of various parameters. The chosen deflection corresponds to the direction of the applied forces, giving a representation of the direct stiffness. For example, when [*LC1*] is applied longitudinally to the load-bearing wall in the z-direction, U3 (the displacement in this direction) will be employed for the analysis. The magnitudes of the deflections are visualised in the Fig. 7.

In load cases [*LC1*] and [*LC3*], the base module shows the greatest overall stiffness. The largest deflection values were observed for the no facade module. The stiffness of the module with part of the facade retained is in between these two cases. The bottom side of the ceiling with the facade had less deflection compared to the side of the ceiling without the facade on the upper side. In

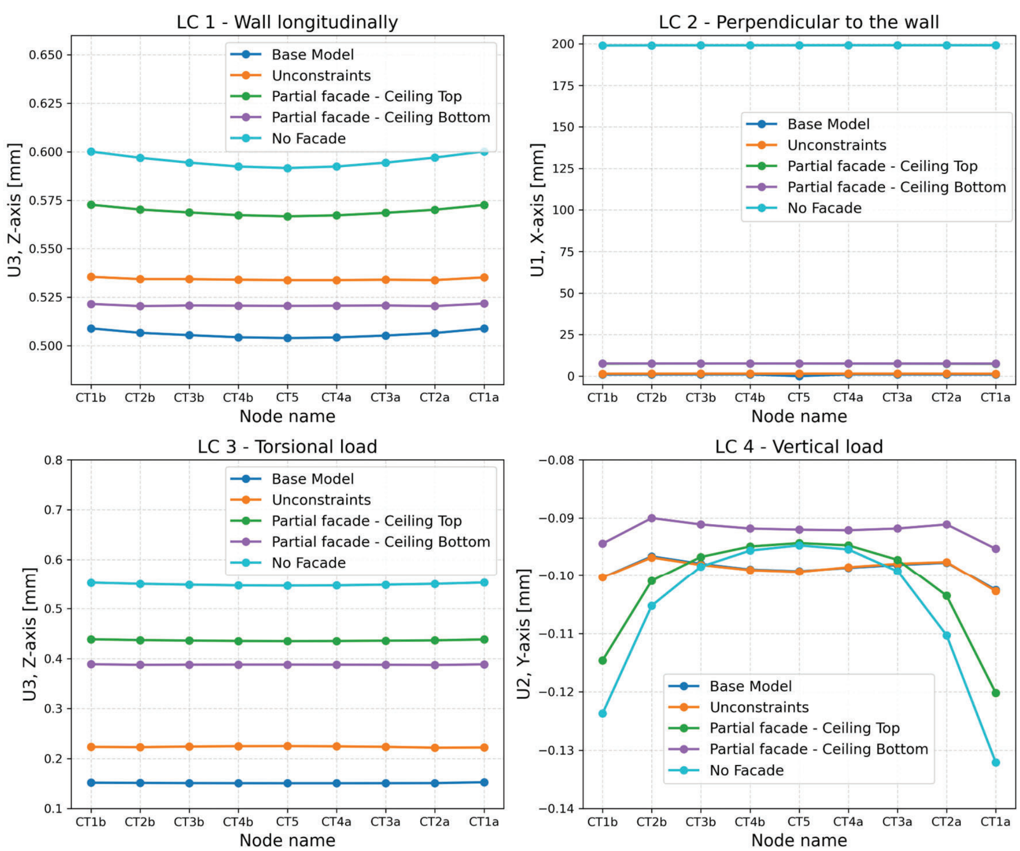

Figure 7. Comparison of deflections at observed nodes of the facade variation models in the four load cases.

[*LC1*], the displacements of the unconstrained module lie between the values on both sides of the partially retained facade module. However, in [*LC3*], the deflection stiffness of the unattached full facade module is greater.

In the scenario where the load is perpendicular to the load-bearing wall [*LC2*], the removal of the facade results in the module losing nearly all stiffness in the x-direction, causing deflection to increase from 1 mm to 200 mm for the base module. The placing of short facades at both ends of the module significantly enhances its structural rigidity relative to a structure free of facades. However, the deflection of the module, with a portion of the facade preserved, remains sevenfold greater than that of the base module. The deflection of the unconstrained module rose by 50 percent relative to the base module. The findings demonstrate that the facade's construction significantly influences stiffness against perpendicular loads.

Furthermore, in the vertical loading of [*LC4*], this comparison shows that the corners present the most significant variation in the overall deflection distribution. The facade wall provides additional support for the exterior corners, and its removal allows for increased deflection. The deflection increases by 24% at the corners in the no-facade configuration and by 15% at the ceiling-top side of the partial-facade module. Additionally, in the partial facade scenario, the deflection on side 'b' exceeds that on side 'a', maybe attributable to the influence of the fasteners' radius. In this context, it should be noted that the fastener approach in ABAQUS is essentially a multi-point constraint, and the radius of the fastener determines the quantity of Gauss points used for the constraint. Any skewness in the mesh or positions of the fasteners can lead to a difference in the "point clouds" that are used in the formulation. A thorough analysis of the fasteners is necessary to ascertain the cause of the asymmetry, but this lies beyond the current study.

4.2 Load-bearing wall variations

According to the stress evaluations conducted in Section 3.3 for [*LC1*] with various opening configurations, module [*Open_1*] has the greatest displacement in this case and the greatest variation in stresses, as seen in Figs. 8 (a) and (b). In contrast to the nodes of other cases, the

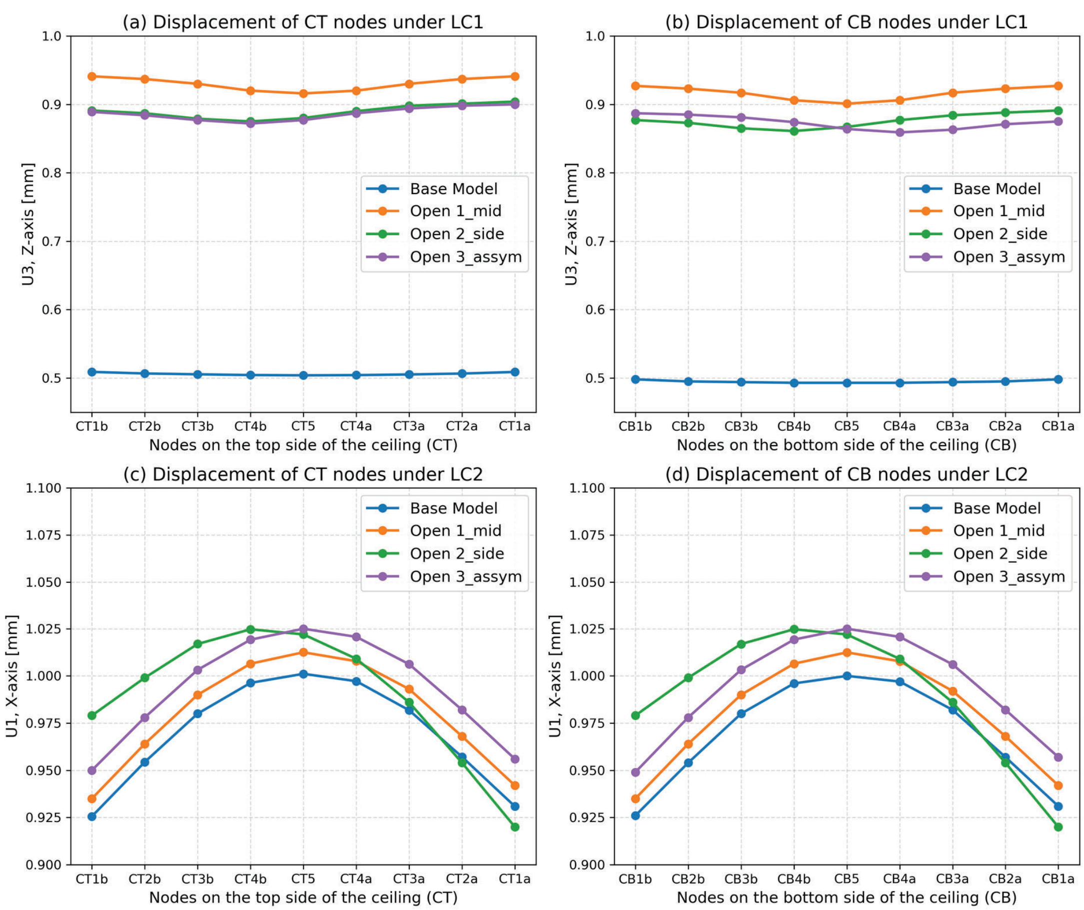

Figure 8. Comparison of deflections at observed nodes of opening variation models for LC1 and LC2.

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[*Open_1*] module exhibits a slightly larger deflection. The only variation between modules [*Open_2*] and [*Open_3*] is the position of the opening in load-bearing wall 1. Fig. 8 (a) indicates that the displacements of module [*Open_2*] and module [*Open_3*] are identical, demonstrating that the position of the openings in the load-bearing wall 2 does not influence the deflection of the load-bearing wall 1.

In the second load case [LC2], where loads are applied perpendicularly to the load-bearing walls, the displacement distribution is the same on both sides of the ceiling, as seen in Figs. 8(c) and (d). All opening configurations exhibited minimal impact on the displacements relative to the result for the base module. In the [*Open_2*] module, the deflection at the opening's location was found to be more significant because of its proximity to the 'b' side. The findings indicate that the optimal position for an opening is centrally located on the wall. However, if the openings are closer to the facade wall, they should be arranged asymmetrically rather than symmetrically.

Like [*LC1*], the openings significantly influence forces in the torsional loading scenario more than in [*LC2*], as the structural load-bearing capacity of this module is predominantly reliant on the load-bearing walls. Figs. 9 (a) and (b) illustrate that the deflection of the model with openings increased by approximately 36% relative to the base module. Nonetheless, a comparison of Figs. 9 (a) and (b) with Figs. 8 (a) and (b) reveal that the deflections of module [*Open_1*] are not significantly different from those of modules [*Open_2*] and [*Open_3*]. This suggests that the location of the openings minimally influences the structural stiffness under torsional loading.

Figs. 9 (c) and (d) illustrate the deflection of the studied module along the y-axis (U2) in reaction to vertical load. The only different trend indicated by the results from the observation nodes on both sides is to the [*Open_3*] module, attributable to the asymmetrical positioning of the openings in the two load-bearing walls. The placement of openings in the load-bearing walls has less impact on the structural stiffness under vertical loading compared to load cases [*LC1*] and [*LC3*].

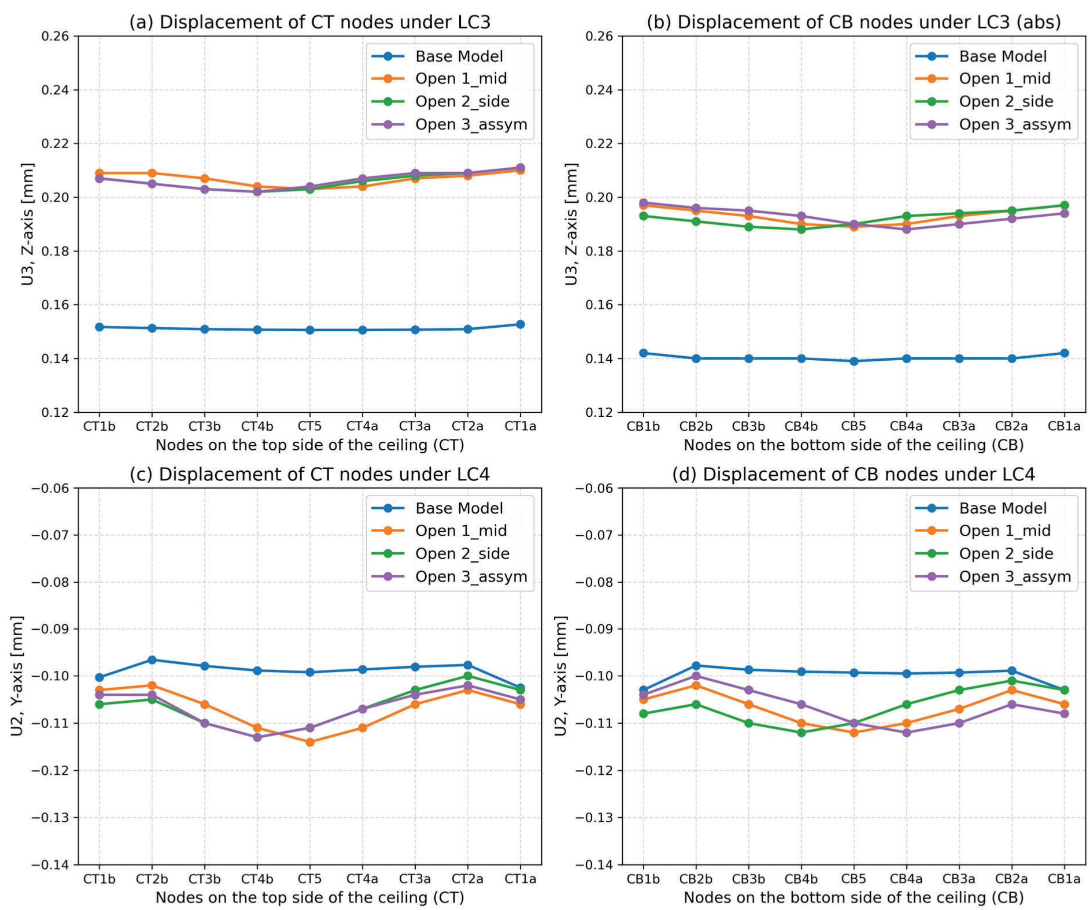

Figure 9. Comparison of deflections at observed nodes of opening variation models for LC3 and LC4.

5 – CONCLUSION

This work aimed to conduct a parametric study of timber frame modules to investigate the impact of various facade configurations and openings in the load-bearing walls on overall structural stiffness.

The standard construction method in Denmark involves constructing modules with a platform frame and placing the wall panels between the floor and the ceiling panels. The wall frames were built with construction timber, while the floor and ceiling were made with glulam frames and Masonite I-beam joist. Mechanical fasteners, including nails, screws, and staples, were used for internal connections.

For the numerical analysis, ABAQUS was utilised as the modelling interface, and Python was employed for parametric scripting. The modelling process began with constructing a single panel, including sheathing panels, angle brackets, and placement of openings. Once all panels were constructed, they were rotated, translated to the desired location and assembled into a comprehensive model. Internal and inter-panel fasteners were then modelled using mesh-independent fasteners and tie constraints. However, discrepancies arose due to the implementation of mesh-independent fasteners. The inconsistent choice of "cloud nodes" by these fasteners led to an antisymmetric distribution in the results despite other interaction types confirming that the geometry and material parameters yielded a symmetric element.

The studied modules were subjected to four different loads, and the stress distributions and the deflection values obtained from designated nodes were compared. Openings to the facade can have a significant effect on the structural stiffness, resulting in module failure, when subjected to forces perpendicular to the load-bearing wall [*LC2*]. This is reasonable, as these facade features significantly contribute to the load-bearing capacity in the corresponding direction. This information is essential for contemporary architectural designs that prioritise wide openings in the facade. Consequently, preserving a portion of the facade achieves a fair balance between aesthetic requirements and structural integrity.

In terms of the influence of load-bearing wall openings, the displacement findings of all opening modules for the basic module vary significantly across all load scenarios. Consequently, there is no ideal selection for the placement of the openings. In [*LC2*], module [*Open_1*] exhibits a minimal increase in deflection, observed at only one percent. This is attributable to its placement relatively far away from the facade wall, which is reinforced by the load-bearing wall. In general, it is preferable to place openings anti-symmetrically rather than at one end of a wall. This is particularly evident in the outcomes for [*LC2*]. This indicates that the asymmetric configuration of openings enables a more effective load distribution balance.

In summary, this study highlights the significance of design decisions while constructing modular timber frame buildings. Optimising facade elements and opening placements can substantially enhance the structural performance of volumetric modular buildings, leading to the development of more robust and reliable modular building systems. Subsequent research should continue the investigation of these elements and their interaction in order to enhance the design and application of modular timber building.

Potential future goals involve investigating the impact of other variables on global stiffness, such as different sheathing options, the addition of angular bracket fasteners at panel corners, and diverse fastener configurations. Although the proposed method is restricted to simulating a single module, it possesses significant potential to be integrated as an embedded component into hierarchical computational modelling frameworks. This will be addressed in subsequent research, focussing on the parametric finite element modelling and structural analysis of modular timber structures.

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7 – CONTRIBUTIONS

Jiayi Kayee Li: Conceptualization, Methodology, Software, Investigation, Illustration, Writing—original draft. **Anne Kristine Bak**: Conceptualization, Methodology, Software, Writing—review. **Laszlo Mangliar**: Methodology, Software, Writing—original draft. **Markus Matthias Hudert**: Writing—review and editing, Supervision. **Lars Vabbersgaard Andersen**:

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Conceptualization, Methodology, Software, Writing—review and editing, Supervision.

All authors have read and agreed to the published version of the manuscript.

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