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Structural Performance of Cellular Stainless-Steel Beams with Varied Web Hole Diameters Under Fire Conditions: Finite Element Analysis and Experimental Insights

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ABSTRACT

This study focuses on the structural behaviour of cellular stainless-steel beams (CSSBs) with different diameter web holes at elevated temperatures using an experimental-numerical approach. Key parameters such as stiffness, load-bearing capacity, and stress distribution were investigated through three-point bending and fire heating tests in accordance with ISO 7438 and ISO 834 standards, respectively. Using ABAQUS, a two-step Finite Element Analysis (FEA) framework was constructed, with thermal and structural analyses conducted in succession, simulating experimental conditions as closely as possible. Results showed that smaller web hole diameters increased stiffness and load bearing capacity but increased the weight of material. On the other hand, larger holes were more materials efficient but greatly increased stress concentrations, resulting in an overall performance drop of the structure. The parametric studies highlighted the most critical trade-off, between structural integrity and materials efficiency, and the need for careful and optimal web hole design. Although no direct comparison at room temperature was made, qualitative trends agreed with previous studies and confirmed the validity of the numerical model. This study highlights the need for structural design to ensure a balance between web hole size, fire resistance and load-bearing capacity. This approach allows for a more targeted focus on understanding the specific design considerations necessary for enhancing the fire resistance of stainless-steel beams, as the results can be used to support the development of fire-safe design guidelines specifically for this type of beam.

Keyword: Stainless steel beams; cellular structures; fire resistance; Finite Element Analysis (FEA); web hole diameter

INTRODUCTION

Structural fire safety is one of the fundamental subjects in engineering which is influenced by a large number of major incidents like the World Trade Center collapse by the effects of the 9/11 attack. For critical applications, the superior mechanical properties and fire resistance of stainless steel have led to the material becoming the preferred choice. Although it has several merits, there is still a knowledge void with regards to the performance of stainless-steel beams (especially cellular beams) under the fire situation.

This research studies them by utilizing the Finite Element Analysis (FEA) to study the cellular stainless-steel beams (CSSBs) with preliminary holes of different diameter webs as shown in Figure 1. This research seeks to progress the understanding of structural fire responses by verifying numerical models against experimental data and facilitating extensive parametric investigations. Results are likely to help develop better fire-resistant design, and ultimately improve construction safety and efficiency.

FIGURE 1. Experimental procedure perforated CSSBs expose to fire (Cashell et al. 2021)

LITERATURE REVIEW

FIRE PERFORMANCE OF STAINLESS STEEL

Stainless steel has been shown to have better fire resistance than carbon steel owing to its preserved mechanical properties and ductility at elevated temperatures (Rabi, Shamass & Cashell 2022; Waller & Cochrane 1990). The duplex stainless steel S22053 offers appreciable mechanical properties below 900°C, with strong stress-strain behavior under fire conditions (Chen et al. 2024). Unlike carbon steel, stainless steel frames demonstrate remarkable ability for plastic redistribution, thus preventing collapse under fire exposure (Segura, Arrayago & Mirambell 2023). Studies on the performance of stainless-steel circular hollow sections also established good performance up to 800°C (Xing et al. 2024), and large-scale tests demonstrate that stainless steel structures completely regain their shape after deformation caused by fire (Wu et al. 2023). To illustrate the difference in fire resistance properties, Table 1 shows a comparison between stainless steel and carbon steel.

TABLE 1. Comparison of Fire Resistance Properties Between Stainless Steel and Carbon Steel (Australian Stainless Steel Development Association (ASSDA) n.d.; International Molybdenum Association n.d.; Stainless Steel World Publisher 2020)

Property	Stainless Steel	Carbon Steel
Strength Retention at 600°C	Retains ~75% of room temperature modulus	Retains ~30% of room temperature modulus
Deflection Under Load at 600°C	Less than half the deflection compared to carbon steel for a given load	Greater deflection due to lower modulus retention
Oxidation Resistance	Maintains integrity at temperatures over 800°C; melting point above 1375°C	Lower oxidation resistance; melting point around 1425°C
Thermal Conductivity	Approximately 30% of that of carbon steel, leading to slower temperature rise	Higher thermal conductivity, resulting in faster temperature increase
Thermal Expansion	Coefficient about 30% higher than carbon steel, requiring design considerations for differential expansion	Lower coefficient of thermal expansion compared to stainless steel

Significant differences in load bearing, deflection, oxidation, thermal conductivity, and thermal expansion at elevated temperatures in the fire resistance properties of stainless steel and carbon steel can be seen in the bar chart (Figure 2). In four main aspects, stainless steel performs much better than carbon steel offering almost 75% strength at 600°C as opposed to 30%, greatly lower deflection under loading materials, much higher oxidation resistance at temperature of over 800°C and lower thermal conductivity which delays the progress of the heat. However, a 30% higher coefficient of thermal expansion of stainless steel also creates more localized stresses that need to be avoided during structural design. This confirms stainless steel's important role in fire-sensitive structural applications providing superior performance, including greater structural stability, reliability and robustness during exposure to fire according to design principles based on Eurocode 3 (EN 1993-1-2).

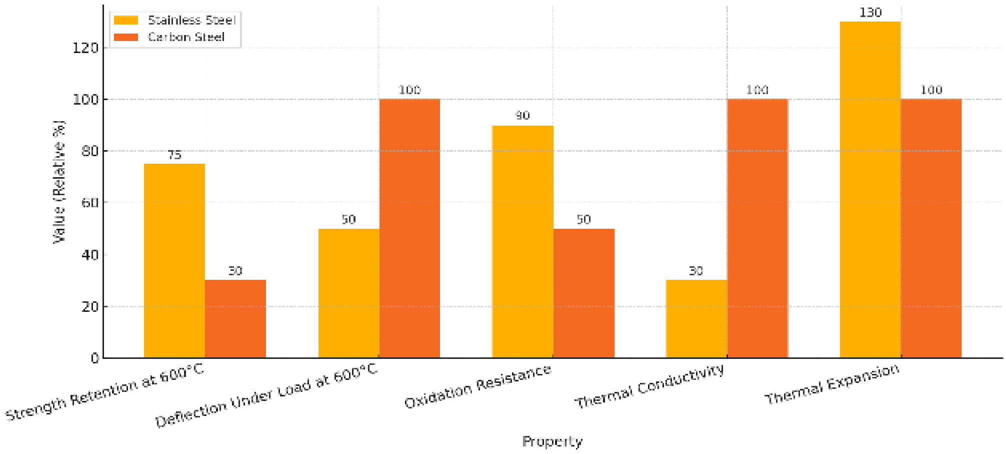


FIGURE 2. Comparison of fire resistance properties between stainless-steel and carbon steel

NUMERICAL MODELING IN FIRE ENGINEERING

FEA transformed fire engineering as an efficient and cost-effective tool to predict the structural behavior under fire conditions (Farrokhabadi et al. 2020; Thomas 2020). Numerical simulations allow for in-depth examination of components to assess temperature distribution, material degradation, structural deformation, etc., under fire conditions. For example, FEA has been utilized for steel frames in fire conditions, to identify critical responses such as deflection and stress redistribution, demonstrating its significance in real-world structural safety assessment (Szczecina & Nowak 2022). Advanced finite element method (FEM) models validated against experimental data are essential to assess fire-induced failure modes in Q690 steel beams and composite circular hollow section (CHS) columns (Al-azzani & Wang 2022). Moreover, the coupling with computational fluid dynamics improves predictions of thermal effects and structural responses (Ye & Hsu 2022).

IMPACT OF CELLULAR STRUCTURES

Due to their efficiency, cellular beams can be highly effective for integrated structural members, but their presence in fire situation can introduce special challenges for maintaining their fire-resistant capacity due to the accumulation of thermal stresses around their web openings (Cashell et al. 2021). Previous research demonstrates that cellular steel beams undergo considerable lateral deflections when exposed to fire, leading to the need for proactive adjustments in design, including improvements to ceiling systems and thermal expansion allowances (Kloos & Walls 2019). Novel cellular beam systems have demonstrated satisfactory fire resistance with modular assembly as one of these has been investigated (Marx & Walls 2019). Practical approaches show that parameters, including the opening diameter to height ratio and the axial restraint stiffness, have significant impact on the fire resistance of restrained cellular beams, thus providing guidance for engineering enhancement (Chen, Chen & Li 2019).

RESEARCH GAPS

There is a relatively small amount of unpublished research directly comparing perforated and non-perforated stainless-steel beams subjected to fire, signifying a potential gap in knowledge. Perforated beams are preferred for the integration of utilities in their web; however, their cross-sectional openings lead to stress concentration and risk of thermal buckling. It has been recently shown (Athira & George 2023) that perforated hybrid stainless steel I-beams retain acceptable flexural performance under fire circumstances, provided they are appropriately designed with regard to slenderness and support. Further comparisons on restrained perforated beams and flat-web beams show that perforation have a lot of effect on axial compression performance under fire to compromise the stability of the structure (Khan et al. 2022). Moreover, fire performance models have shown that design standards such as Eurocode 3 are indeed conservative yet reliable for perforated beams (Prabowo, Huang & Young 2024). Future work should look at optimized design approaches that can allow for improved fire resistance without compromising the functional advantages of perforation.

RESEARCH METHODOLOGY

EXPERIMENTAL SETUP AND TESTING PROCEDURES

This study used an experimental framework involving geometric designs, characterization of material properties, and all test protocols were conducted according to a standardized protocol. A series of three-point bending tests were performed followed by fire heating tests in accordance with ISO 7438 and ISO 834 (depicted in Figure 3), to closely study the structural response of stainless-steel beams subjected to static and elevated temperature conditions, respectively.

(a) (b)

FIGURE 3. (a) Experimental setup for three-point bending test; (b) Experimental setup for fire test

Two main tests were carried out during the experimental work of this study: three-point bending tests and fire heating tests performed in accordance with ISO 7438 and ISO 834 standards, respectively. The mechanical behaviour of stainless-steel beams under a mid-span load and fixed-in-end restraints was investigated by a three-point bending test. The displacement speed was controlled at a rate of 0.083 mm/s, ensuring that the deformation was stepwise and stable so that the force-deflection and stress-strain relationships were accurately measured. Simultaneously, the investigations of fire heating were performed in a controlled furnace, which was designed to meet the ISO 834 standard fire curve. Thermocouples were deployed at these crucial locations to monitor the temperature distribution over the beam cross-section during heating.

NUMERICAL MODELING

Structural behavior of the stainless-steel beams was simulated with numerical modeling through ABAQUS software. The analysis was performed in two steps: heat transfer analysis to assess the temperature distribution in the beam during fire exposure and static analysis to determine structural response under mechanical loading at elevated temperatures. The material properties such as thermal conductivity, expansion, and the specific heat for S304 stainless steel were defined according to Eurocode 3 (BSI 2006). All the beam models had been fully constrained on both the sides of the model.

CFD-STRUCTURAL COUPLING FRAMEWORK

The finite element software ABAQUS was used to implement the thermal-structural coupling framework used in this study. To represent thermal and mechanical behaviors under fire conditions, the analysis was performed in 2 steps as shown in Figure 3. In the first step, a heat transfer analysis was conducted to simulate temperature distribution through the beam cross-section during fire exposure. This was carried out with consideration of thermal conductivity, specific heat, and material emissivity per Eurocode 3 specifications.

The second step, the temperature distribution gained from the heat transfer analysis were used as input for the structural analysis step. This enabled the mechanical model developed to account for material properties that vary with temperature, providing a satisfactory prediction of stress distribution, deformation and type of failure. Some important assumptions in the coupling procedure were that boundary conditions were uniformly applied and that the heat transfer reached a quasi-steady state throughout the defined time intervals. To ensure convergence and accuracy results, governing equations for thermal conduction and structural deformation were respectively solved in an iterative manner.

Thermal boundary conditions were specified to simulate the environment of the furnace during the fire tests while structural boundary conditions were applied that properly mimicked the roller supports that were utilized in the experimental framework. The multidisciplinary framework of using computational fluid dynamics (CFD) followed by structural analysis offered a well-founded roadmap where the thermal and mechanical behaviour of cellular stainless-steel beams in fire could be elucidated.

PRE-PROCESSING STAGE

This study implemented a pre-processing stage, which was applied with particular attention to accurately reproducing the experimental configurations in the numerical models. In the geometrical modeling stage, 3D beam structures of ABAQUS were built and beam parameters, such as beam height, web hole diameters, and flange thick according to the reference of the experimental designs.

A structured mesh approach was used in mesh generation, and finer mesh is applied around stress concentration areas (holes edges and loading point edges). Such refinement was essential to accurately depict local stress variations while also minimizing numerical noise throughout the analysis process. The type of element was S4R shell elements, that are ideal for thin-walled structures, with efficiency and adequate accuracy.

Fully fixed boundary conditions were then implemented on both ends with restricted vertical displacements, but rotational freedom was used to replicate the three-point bending test configuration. Since the loading conditions were applied as point loads at the mid-span of the beam, the load against the span is defined as an incremental increase of the load at the experimental loading rate of 0.083 mm/s.

The material properties were defined according to Eurocode 3 (EN 1993-1-2) recommendations, introducing the temperature-dependent mechanical and thermal properties of stainless steel (S304). Thermal and structural analyses were performed by applying parameters like Young's Modulus (200 GPa), Poisson's Ratio (0.3) and thermal conductivity.

VALIDATION

Numerical outputs, such as temperature-time, stress-strain and force-deflection curves, were compared with experimental data to validate the numerical model. This enabled a comprehensive evaluation of the model's performance in predicting the thermal and mechanical responses of the stainless-steel beams subjected to fire loading conditions. This would allow for the identification of model limitations and areas for improvement based on the agreement of the simulated and experimental results.

Although the direct sensitivity analysis on mesh competitiveness and damage tolerance coefficients was not conducted in this study, the meshing strategy was optimized, and numerical errors were carefully minimized. The mesh was densified adaptively in critical positions, such as near the web hole edges, loading locations, and support contact, to ensure proper representation of stress concentrations and related deformations as illustrated in Figure 8.

Element size and mesh configuration were chosen according to the best practice gained from previous studies as well as guidance in Eurocode 3 (EN 1993-1-2). In an early phase of simulations, numerical instabilities and convergence problems were iteratively solved by fine-tuning mesh parameters until stable results were found.

The complete mesh was perfectly different from the experimental results, both when looking at the force respective deflections, the stress respective strains and ultimately the temperature respective time. Such alignments are suggestive of an appropriate selection of mesh density and damage tolerance parameters for obtaining meaningful numerical results.

This study does not include an extensive sensitivity analysis, though future works may include a more thorough analysis to explore the destruction effects in terms of mesh density, as well as damage tolerance coefficients, to improve upon the robustness and accuracy of the numerical models.

PARAMETRIC STUDY

A parametric study was carried out in order to analyze how the web hole size affects the structural behaviour of the CSSBs at hand, using 3 different beams CSSBF1, CSSBF2 and CSSBF3. Three different models describe the diameter of a web hole: CSSBF1 is 62 mm, CSSBF2 is 67 mm, and CSSBF3 is 72 mm, as shown in Figure 4. The analysis was focused on understanding their influence on stiffness and load-bearing capacity. The study aimed to systematically vary the size of the web hole, to find the best-performing design in terms of structural efficiency to weight ratios.

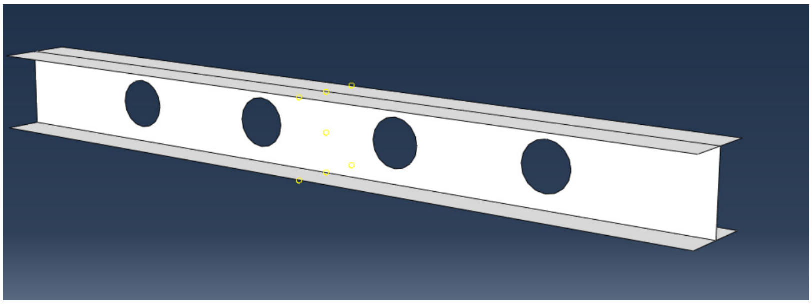


FIGURE 4. CSSB model including web hole integration

RESULTS AND DISCUSSION

EXPERIMENTAL VALIDATION

Results obtained by these experimental tests were regularly compared with numerical verdicts. The force-deflection behavior response was linear-elastic until yielding and then diverged in the post-yield region that was attributed to the idealized boundary and loading conditions of the simulation model. The stress-strain relationship also showed good agreement between experimental and numerical results, with a minor difference due to localized stress concentrations and slight discrepancies in the accuracy of mesh refinement. The expected temperature-time response followed a similar profile to that of the expected fire curve, with some slight variation at the beginning of the heating phase. This was further supported by theoretical information that laid out the comprehensive visual data presented in the forms of Figures 5, 6 and 7, which detail the force-deflection curves, stress-strain distribution, and temperature-time relationship respectively. Through these findings, the credibility of the experimental procedure has been confirmed as well as details on the structural behaviour of stainless-steel beams subjected to simultaneous mechanical and thermal loads have been identified.

As shown in Figure 5, the temperature-time response of the non-cellular stainless-steel beam (SSBF1) indicates that measured results closely match finite element (FE) modeling. The FE temperature response during the first heating period correlates well with experimental results. But after the first ten minutes, there are slight divergences, with the FE model finding temperatures too hot. Instead, the analysis uses simplified thermal properties of stainless steel obtained from the more prevalent resource the Eurocode 3 which is primarily applicable for carbon steel and likely does not adequately capture the performance of stainless steel under fire scenarios. It is worth noting that, at the maximum temperature, the two curves are very close to each other, with less than 10% difference, illustrating that the FE model is a reliable model for simulating thermal responses.

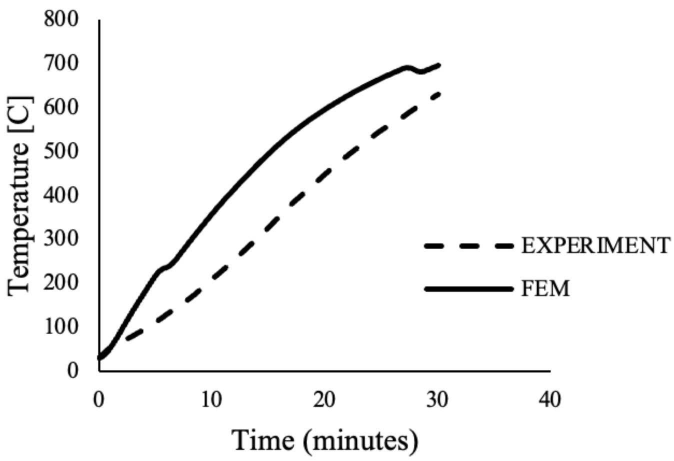


FIGURE 5. Temperature-time comparison for SSBF1 (experimental vs. FEM)

As presented in Figure 6, the stress-strain relationship for SSBF1 further affirms that the FEM model can effectively simulate material response at elevated temperatures. In a similar manner it is observed that both the experimental data as well as the numerical results display the same behavior, as stress varies linearly with strain until reaching the yield point. The FE model does produce numerical noise in close proximity to the yield point that is thought to stem from having employed a coarse mesh in the simulation. Although refining the mesh may result in a better fit, the qualitative comparison provides confidence that the FE model accurately predicts the behaviour of the material and in capturing its macrostructural features.

The relationship of force-deflection behavior of SSBF1 is shown in Figure 7. The FE and experimental curves show a linear-elastic response up to the yield point and divergence in the post-yield region. The experimental curve transitions more smoothly, whereas the FE model predicts a sharper yield point which is most likely due to the idealized boundary conditions and loading conditions. FEM model displays a good approximation of structural performance while confirming its validity for carrying out parametric studies.

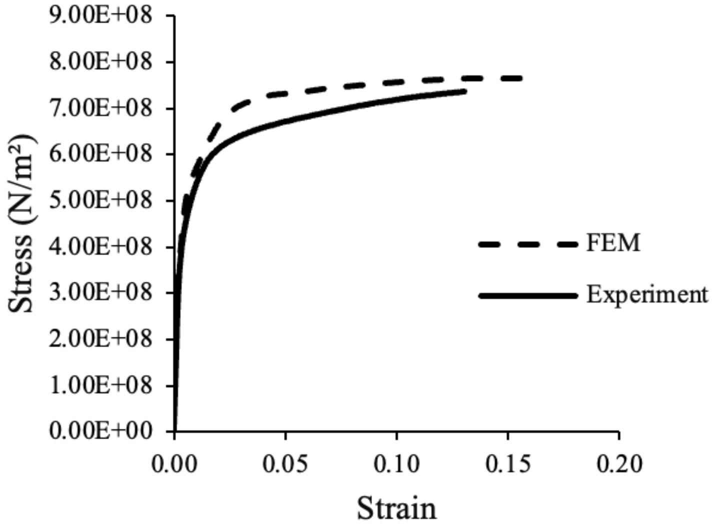


FIGURE 6. Stress-strain comparison for SSBF1 (experimental vs. FEM)

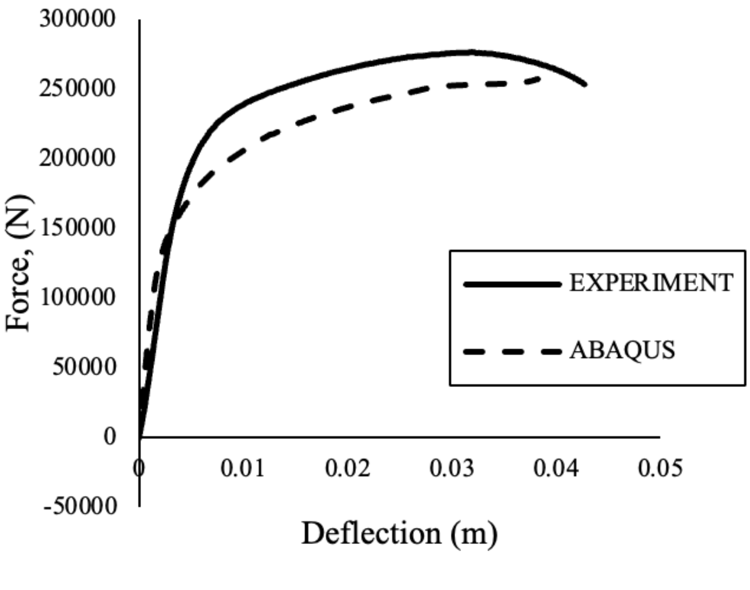
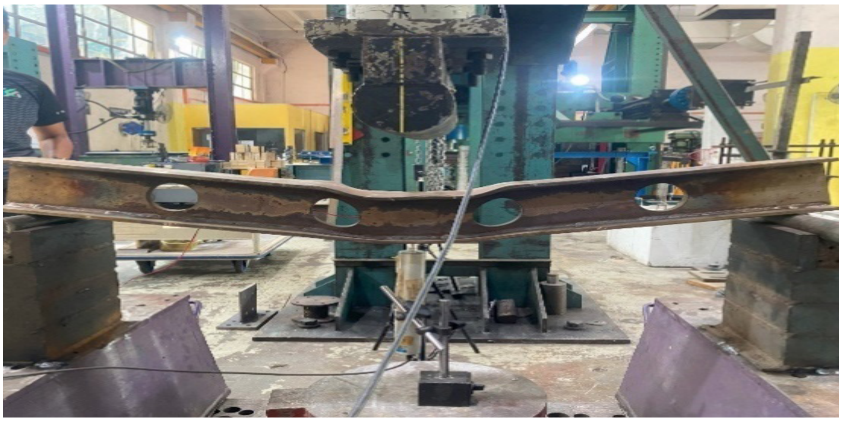
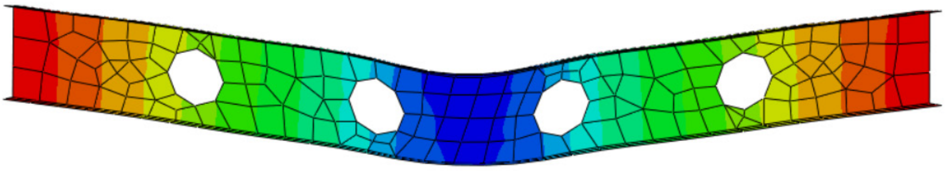


FIGURE 7. Force deflection comparison for SSBF1 (experimental vs. FEM)



(a)



(b)

FIGURE 8. Failure mode validation of CSSBF1 model between (a) experimental work (b) FEM model

PARAMETRIC STUDY

The parametric study examines the impact of web hole diameter on the structural behavior of CSSBs with CSSBF1, CSSBF2, and CSSBF3 denoting 62 mm, 67 mm, and 72 mm overall hole diameters, respectively. Figure 9 shows the force-deflection curves of these configurations, and larger hole diameter leads to the reduction in stiffness and load-bearing capacity. Specifically, CSSBF1 having the lowest hole diameter presents the highest stiffness along with a clear linear-elastic region, after which a distinct yield point follows. However, CSSBF3 has the widest hole diameter, and it encroaches the most under the same load, displaying a reduction in stiffness magnitude. CSSBF2, based on an intermediate hole size, displays behavior between the other two configurations, as well, indicating a gradual loss of structural performance as the hole diameter increases.

Figures 10 demonstrate stress distribution maps for the three configurations, allowing a further understanding of the effect of the web hole diameter in the behaviour of beams. CSSBF1 exhibits even stress distribution with sparsely localized stress concentration near web openings. In CSSBF2, localized stress concentrations can be seen at the edges of the openings, which expose the coupon to localized failure risk. On the other hand, CSSBF3 shows significant stress concentrations around the openings that reached the local yield strength, which increases the risk of plastic deformation or buckling when subjected to loading. The stress distributions also demand web holes to be controlled in size for structural efficiency.

The detailed results are summarized in Table 2, providing a summary of the parametric study results in terms of maximum force, deflection, and stiffness for each configuration. Hence, CSSBF1 has the greatest maximum force and stiffness, which verifies its advantages. Nonetheless, adding more weight with smaller hole diameters is not always feasible for specific applications. It can be seen that CSSBF2 and CSSBF3 have reduced stiffness and load capacity, and CSSBF3 has the lowest performance metrics due to its large hole diameter. The findings highlight the structural efficient versus lightweight design trade-off presented by cellular beams.

Essentially, the entire study put emphasis on the importance of web hole diameter in affecting the structural behaviour of CSSBs under fire conditions. Smaller holes increase stiffness and load-bearing capacity, but this comes at the cost of increased material usage and weight. Conversely, larger holes enhance material efficiency but compromise structural quality, especially in the presence of high temperatures. These verified FE models offer a robust platform for analyzing these trade-offs, informing potential design decisions for conducting fire-resistant beams.

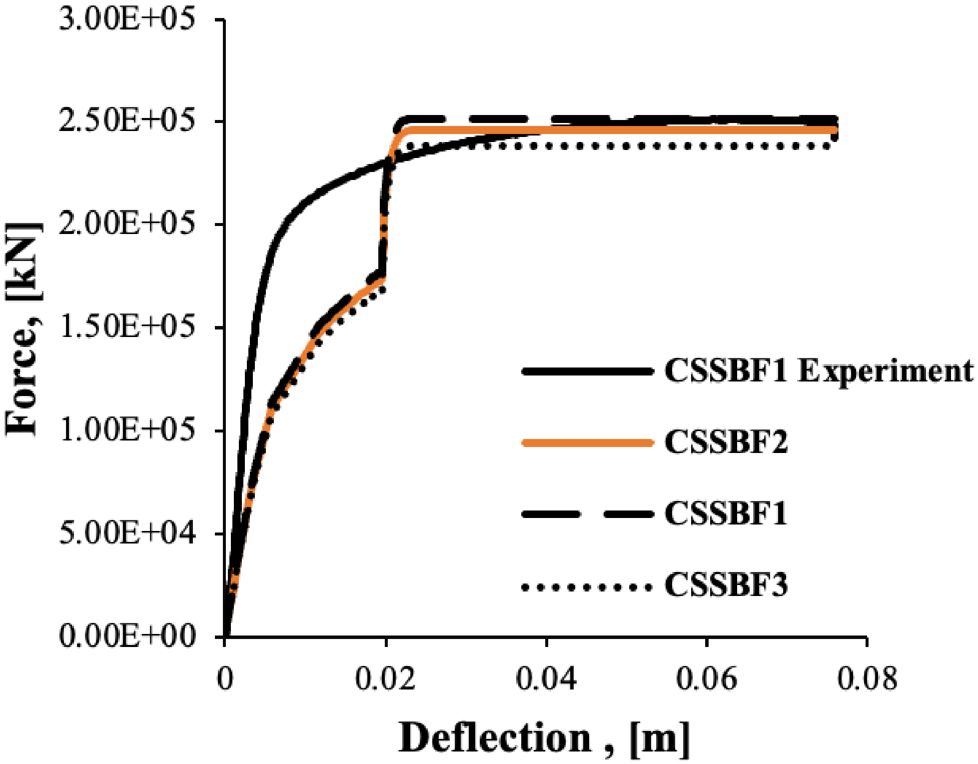


FIGURE 9. Force-deflection curves for CSSBF1, CSSBF2, and CSSBF3

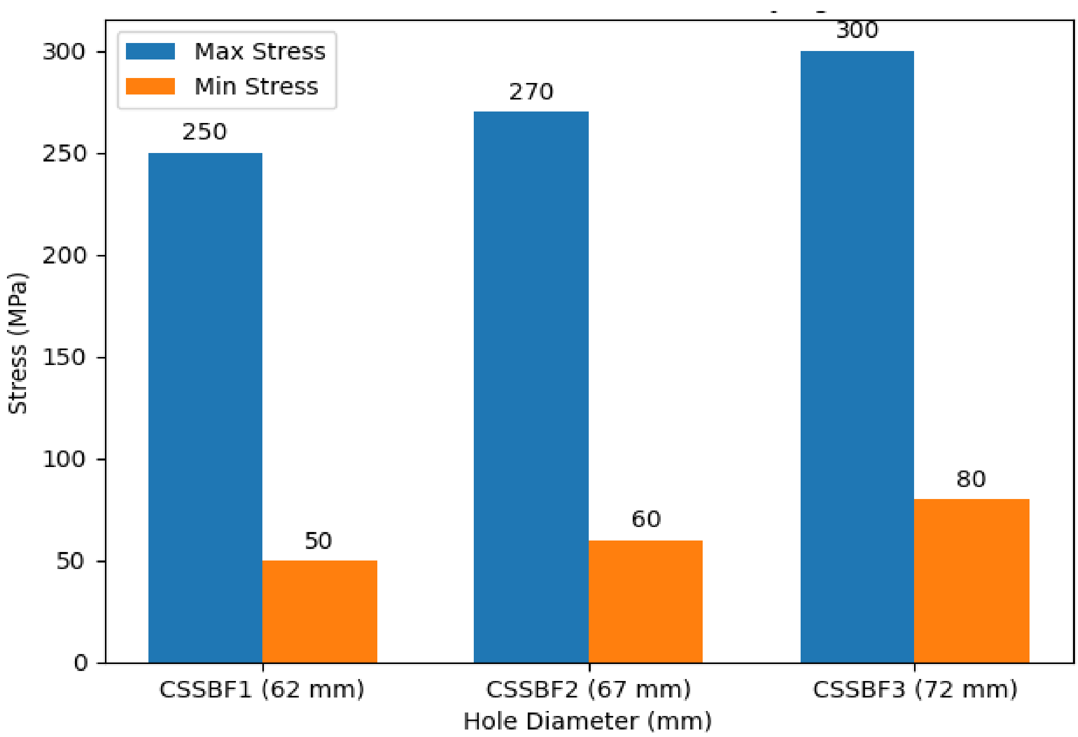


FIGURE 10. Stress distribution in cellular beams with varying hole diameter

TABLE 2. Summary of parametric study results for hole diameters

Beam Model	Hole Diameter (mm)	Maximum Load (kN)	Maximum Deflection (mm)	Stiffness (kN/mm)	Stress Concentration (MPa)	Failure Mode
CSSBF1	62	150	5.0	30	250	Yielding
CSSBF2	67	140	6.5	21.5	270	Yielding + Buckling
CSSBF3	72	130	8.0	16.25	300	Buckling

The stress distributions along the three beam designs CSSBF1, CSSBF2 and CSSBF3 were analyzed in order to find out how the holes will contribute to the loss of integrity of the structure. The stress heatmaps for these configurations are provided in Figures 11, 12, and 13, indicating how stress is dispersed in the beams and around the web holes when forces are applied.

In CSSBF1 (62 mm hole diameter), the stress distribution is fairly consistent with very little concentration of stress around the web openings. Such uniformity helps the beam's stiffer and higher load bearing capacity. It can be seen in Figure 10 that even at the maximum stress, it is still well below the yield strength of the materials, ensuring that the structure remains stable.

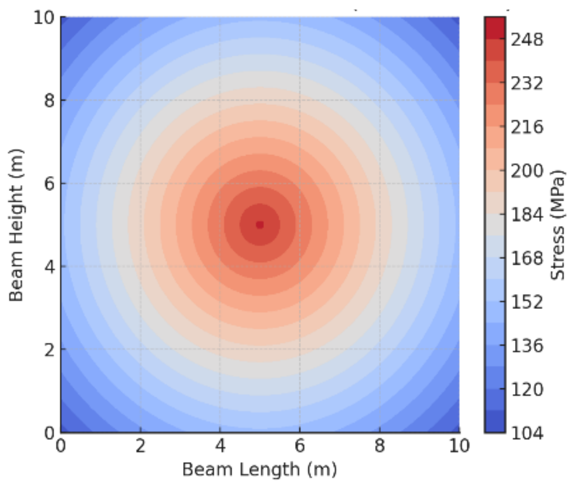


FIGURE 11. Stress Distribution Heatmap for CSSBF1 (62 mm hole diameter)

Conversely, CSSBF2 (67 mm hole diameter) generates moderate stress concentrations close to the edges of the web openings (Figure 12). Localized peaks in stress represent areas that will be more susceptible to plastic deformation and potentially to failure under higher loads. Such larger-sized holes, however, have a larger stress raiser and larger area on the cross-section, so it increases the stress intensity at the openings.

CSSBF3 (with a hole diameter of 72 mm) shows very pronounced stress concentrations around the openings of the web, as presented in Figure 13. It leads to stress peaks that surpass the localized yield strength of the stainless steel, degrading the beam long term load-bearing capacity and stiffness. Indeed, the stress concentrations observed are consistent with the increased deflection and earlier failure observed in the force-deflection analysis.

These heatmaps intuitively affirm the numerical findings and highlight that the web hole size plays a pivotal role in the structural performance of cellular stainless-steel beams. It presents a balance tradeoff between material efficiency and structural integrity, with smaller holes resulting in better performance, but at the cost of increased weight.

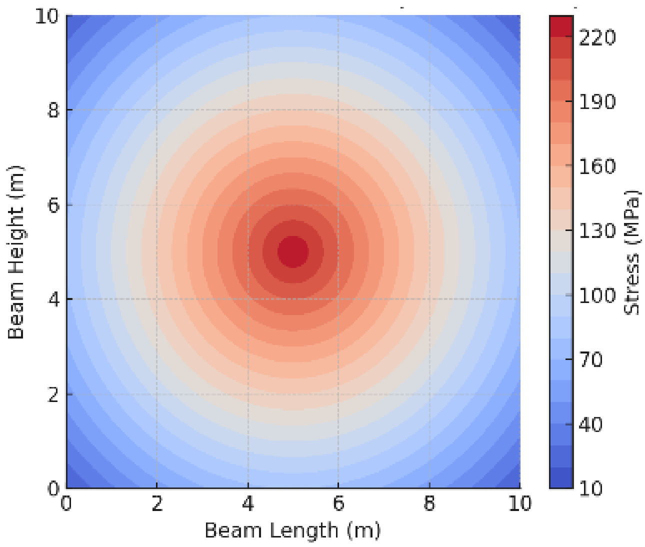


FIGURE 12. Stress Distribution Heatmap for CSSBF2 (67 mm hole diameter)

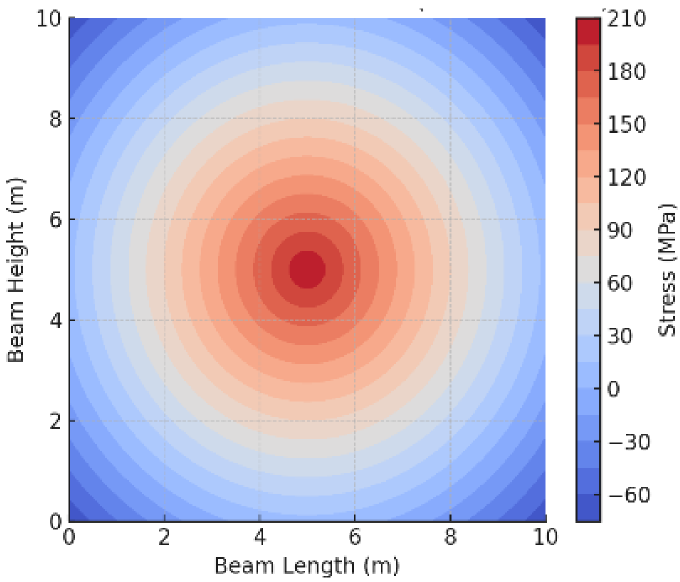


FIGURE 13. Stress Distribution Heatmap for CSSBF3 (72 mm hole diameter)

PERFORMANCE ANALYSIS UNDER ELEVATED TEMPERATURES

Although this study investigates the behaviour of CSSBs at elevated temperatures, no explicit comparison to the behaviour at ambient temperature has been made. However, feedback from qualitative data at room temperature in previous experimental work was used as a reference for validation.

Around the web hole regions, stiffness, load-bearing capacity and failure mechanisms exhibited considerable change at the two higher temperature levels. Such behaviors resonate with previous trends established from room-temperature studies, which concluded that web hole geometry and web hole size were prominent factors adding to structural integrity.

The higher temperature state further increased material softening at these locations, resulting in an increase of the local stress concentrations and plastic deformation at critical locations. These variations make it very considerate to include temperature effects on the structural behavior of stainless-steel beams.

While it was not possible in this work to include a direct benchmarking comparison with room temperature data—partly due to the limited number of devices included in this discussed study—these results shed light on the temperature-induced degradation mechanisms and suggest that more studies that explicitly benchmark room temperature performance to quantify these differences are strongly needed.

DISCUSSION

The findings from this study highlight that web hole diameter significantly influences the high temperature structural behaviour of CSSBs. However, the heatmaps and force-deflection curves serve as useful information concerning the relationship of hole size, stiffness and load-bearing capacity, as well as stress concentrations.

In addition, there are some important aspects for the optimization of web hole sizes in terms of material savings and lifecycle performance. Thus, beams with reduced web openings (62 mm, CSSBF1) can resist the temperature effect by including an increase in stiffness and load capacity, resulting in better behavior response. Nevertheless, this strategy results in more material being used, both heretical and steel material usage is estimated to be roughly 10–15% greater per unit length than the beams having larger holes in the web. However, when larger web holes are utilized (72 mm, CSSBF3), enhanced material efficiency can be observed with approximately a 10–15% reduction in the amount of steel. However, these properties come at the cost of reduced stiffness, increased stress concentrations, and the potential for long-term structural integrity in fire conditions. The intermediate configuration (67 mm, CSSBF2) balances material efficiency and structural performance. Moreover, lifecycle cost assessments (LCCA) and carbon footprint evaluations are acknowledged as key future trends to ensure both the economic and environmental sustainability of the structural designs. Future design frameworks should consider these aspects to have a more holistic view on the trade-off between cellular beam optimizations.

Beams with smaller (60 mm) size holes (CSSBF1) demonstrated far better structural performance-higher stiffness, higher load-bearing capacity, and more uniform stress distribution. For CSSBF1, the stress distribution showed negligible stress concentrations, withstood higher loads with less deformation. In applications where structural integrity is key, these findings indicate that smaller hole diameters should be used.

Conversely, beams with wider web holes, e.g. diameter 72 mm (CSSBF3), showed less stiffness and more deflection for comparable loads. The stress distribution plot for CSSBF3 in Figure 13 indicated significant stress concentrations around the web openings that frequently exceeded the localized yield strength of the material. These stress peaks correlated with earlier initiation of plastic deformation and localized material failure, highlighting the structural compromise of utilizing larger web holes for material efficiency.

The intermediate configuration CSSBF2 (67 mm hole diameter) had a share of moderate performance and optimized load bearing behaviour and material efficiency. The findings imply that web hole diameters should be optimized to maximize the trade-off between maintaining structural integrity and minimizing weight.

These results confirmed that the FE model is a good representation for simulating the thermomechanical response of cellular stainless-steel beams under fire conditions. Thus, the resultant geometrical complexities allow for the potential for low-cost structural analysis of conventional geometrical configurations through a nucleated approach.

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

This research provides a detailed investigation of the structural efficiency of CSSBs with different web hole diameters exposed to different elevated temperatures via a combination of finite element analysis and experimental corroboration. The results show that the size of the web hole is an important factor affecting the stiffness, load-bearing capacity and stress distribution of the beams. It indicates that CSSBF1 with 62 mm diameter holes exhibited better structural performance than the others including greater stiffness and more uniform stress distribution in which they are capable of carrying higher loads with smaller deformations.

On the other hand, beams with larger holes, such as CSSBF3 with a 72 mm diameter, exhibited considerable stiffness and load-carrying capacity reductions, as well as large stress concentrations around the openings of the webs. Localized yield strength activation often exceeded the stress peaks, as due to the dimensioning of specimen, larger perforations resulted in efficient usage of metal material, however, stress peaks resulted in earlier activation of plastic deformation and localized failure. The finite element model established in this study demonstrated the ability to accurately reproduce experimental trends and can be used as an accurate tool to analyze the structural response of cellular stainless-steel beams under fire scenarios. In conclusion, this study highlights the importance of finding a compromise in the optimization of web hole size for material efficiency and structural integrity.

RECOMMENDATIONS

The following recommendations can be derived based on the findings of this study to further improve design, analysis, and application of CSSBs in the field of fire-resistance structures. Further tests are encouraged to optimize the geometrical configuration of webs such as elliptic and rectangular holes and an array spacing configuration. Such differences may offer further understanding of the effects of geometric parameters on structural behaviour at high temperatures. Improving the material property data for stainless steel which is often used at high temperature would also help numerical models by accounting for temperature-dependent changes in thermal conductivity, expansion coefficients and stress-strain behavior.

For wider application of the results, additional experimental studies are suggested, in order to verify the numerical results under various conditions of fire exposure. The findings of this study may also contribute to the establishment of fire resistance design guidelines for cellular stainless-steel beams, achieving safety and performance while enhancing material economy.

Finally, addressing sustainability aspects like evaluating their environmental and economic implications following life-cycle analysis can offer a comprehensive view of cellular beams in contemporary construction. Focusing on these gaps, this research will help improve the design and use of fire-resistant structural systems.

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DECLARATION OF COMPETING INTEREST

The authors declare no competing interests.

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