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Behaviour of cellular steel beams subjected to impact load: A review

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Abstract

The service life of structural buildings may encounter dynamic loads such as impact and explosion loads, which can occur accidentally, such as vehicle collisions or explosions. As a result, studying the structural behaviour of members in dynamic scenarios is essential. In addition, the incorporation of web openings in these members is an important aspect of structural engineering. However, It leads to a complicated of factors that greatly influence the overall performance and behaviour of the structure. The purpose of this article is to review the studies on the primary factors affecting the dynamic behaviour of the cellular steel beams under impact loading. This will be accomplished by discussing experimental, numerical and analytical studies. Also, the utilized guidelines in designing buildings to resist impact loads were reviewed. The study found that incorporating a slab greatly enhances the load-bearing and shear strength of a composite beam when subjected to impact, surpassing that of a steel beam without a slab. The size and positioning of web holes greatly affect the behaviour of perforated steel beams, especially the stress distribution in these beams.

Keywords: *Cellular beams, elongated web openings, impact load, composite beam, slab thickness.*

1. Introduction

Steel structures are essential in today's construction because they meet the needs for efficiency, safety, and adaptability [1], [2], [3]. More precisely, they offer a cost-effective construction solution with efficient manufacturing, low maintenance requirements, aesthetic appeal for architects, and a strong ability to withstand tough weather and extreme forces. However, this exceptional strength may not be fully utilized due to restrictions on allowable deflection limits. In recent years, modern steel buildings have undergone continuous development, securing a growing significance in numerous high-rises and long-span projects. As a result, structural engineers have made several attempts to develop methods for reducing the costs associated with steel construction, as mentioned in [4]. Different innovative strategies have been implemented to enhance the stiffness of steel structures without the requirement for additional steel. Incorporating web openings in steel beams is considered one of the many methods in the development of steel structural systems [5] as shown in Figure 1.

Openings are a common feature in the structural steel beams of multi-level structures. to allow pipes, ducts, and electrical cables to pass through [7]. Accordingly, the total height of the construction area will be reduced, leading to lower expenses for the structure. In most cases, cellular beams with various types of web openings are less stiff than solid beams, leading to greater deflections [8-10]. Also, including these openings reduces its shear and flexural strength [11-13]. In light of this, several investigations have been to assess the behaviour of perforated steel under various loading scenarios.

The static response of structural members has been the subject of comprehensive research, resulting in valuable guidelines for structural engineers to improve the resistance of members to static loading. Nevertheless, these guidelines were used to design the Ronan Point Building in London, which collapsed in 1968 as a result of a gas leak in one of its 22 floors. The collapse of the upper apartment caused a strong impact that the floor couldn't handle. As a result, the entire structure underwent successive destruction, leading to the collapse progressing until it reached the ground [14-16] as shown in Figure 2. In other words, it can happen when an upper floor falls onto a lower one, known as the "falling floor scenario" [17-18], creating dynamic forces on the lower floor. To minimize or prevent progressive collapse, structural engineers implemented updates to existing regulations. Despite these updates, the ability to prevent progressive collapse was limited, especially when facing a variety of terrorist attacks that could compromise even the strongest structures such World Trade Center (USA, 2001), (bomb of Madrid, 2004), and (Mumbai terrorist attack, 2008). Hence, the dynamic behaviour of structures raised significant concerns.

Several studies were carried out to enhance the current guidelines on withstanding impact and explosions, to gain insights into the behaviour of various structural components under such loads. The main subjects of these studies included floor collapse impact and the resulting catenary action [19-22]. Even so, under impact and column removal conditions, different kinds of slabs, beams, and beam-column connections were investigated [23-30]. Research has shown that beams are more effective in withstanding impact load than slabs and connections. Hence, over the past ten years, there have been attempts to examine the impact of load on steel beams.

This effort aims to enhance our understanding of how these elements react under intense loading conditions [19, 32-33], [34-35]. Some researchers have explored the potential of solid and perforated steel beams [36-37] To mitigate the risk of progressive collapse caused by floor impact. This review aims to investigate the effect of key parameters including slab thickness, and aspect ratio of openings on the dynamic response of composite beams subjected to an impact load.

Fig. 1: Renovation using perforated beams at the headquarters of Crédit Lyonnais, Paris [6].

Fig. 2: The collapse of Ronan Point, 1968 [31].

2. Design codes of impact load

Impact load is a term used to describe a sudden force or load on a structure or component. Impact loads, unlike static or sustained loads, are short and can result in sudden changes in stress, deformation, and structural response. Impact loads are typically caused by dynamic events, such as accidents involving construction equipment, falling rocks from mountains that affect nearby facilities, collisions between ships and marine structures, debris from explosions, objects falling from one floor to another, and aircraft landings on different surfaces. Design codes for impact loading are standards that provide guidelines for designing structures to account for the impact load. These codes are essential to ensure the safety and durability of structures subjected to impact loads. Furthermore, this section explains some of these codes.

2.1. BS EN 1997-1-7 (2002)

The code addressed accident actions resulting from various events, such as impacts with road vehicles, forklift trucks, trains, ships, and the rough landing of helicopters on roofs. It guided the representation of actions and defined design values for the impact scenarios. Furthermore, it has provided a method to reduce or handle the consequences of impact scenarios. The approach utilized in this code involves converting impact forces into equivalent static forces. In addition, under this code, impacts are classified as either hard or soft.

2.1.1. Hard impact

In this scenario, the impacting body primarily dissipates energy. A simplified model was implemented to determine the equivalent static forces in cases of hard collisions, assuming that the colliding body deforms linearly during the collision. The formula for predicting the equivalent static force is as follows (equation 1):

$$F = V\sqrt{km} \tag{1}$$

As shown, "m" represents the mass of the impacting object, "k" signifies its associated elastic stiffness, and "V" denotes the velocity of the object at the moment of impact.

2.1.2. Soft impact

The structure is specifically designed to dissipate the impact energy through elastic-plastic deformations of its members. This means that the structure can deform to absorb the impact energy, showing ductile behaviour. According to the code, the structure under impact is considered to be elastic, while the impacting object is assumed to be rigid. When the structure reaches its limit and undergoes a rigid-plastic response, the specified condition is fulfilled by the following expression (equation 2):

$$F_0 y_0 = \frac{1}{2} m v^2 \tag{2}$$

F_0: the maximum value of the static force.
y_0: the maximum displacement of the point of impact that the structure can withstand.
Additionally, the code offers detailed tables containing equivalent static design values for different impact scenarios. Despite this, there was no analytical model available to forecast the impact response of steel beams with web openings.

2.2. TM5-1300

This manual is still actively used in the USA. It provides guidelines for assessing blast effects from explosions and methodologies for structurally designing buildings to withstand these effects [38-39]. The structural systems were classified as donor, receptor or acceptor, and protective systems. The deformation criteria were determined by considering the type of system and the typology of the structural element.
To ensure the integrity of the beam element, the permitted deformation was limited to 12-degree support angle rotation (i.e., represents the angle formed by the chord, which connects the supports, and the spot on the element where observed displacement reaches its maximum). Ductility is a crucial factor as it allows structures to undergo large deformations and redistribute loads, especially enhancing their ability to withstand explosive forces. The code recommends using tables to calculate the design stress based on the ductility ratio for various structural elements. However, the ductility beam ratio should be higher than 20 as specified in the code. However, adequate bracing is necessary to support the elevated ductile behaviour effectively. Also, The TM5-1300 emphasizes that to design steel buildings with narrow geometries, addressing local or global instability is crucial.

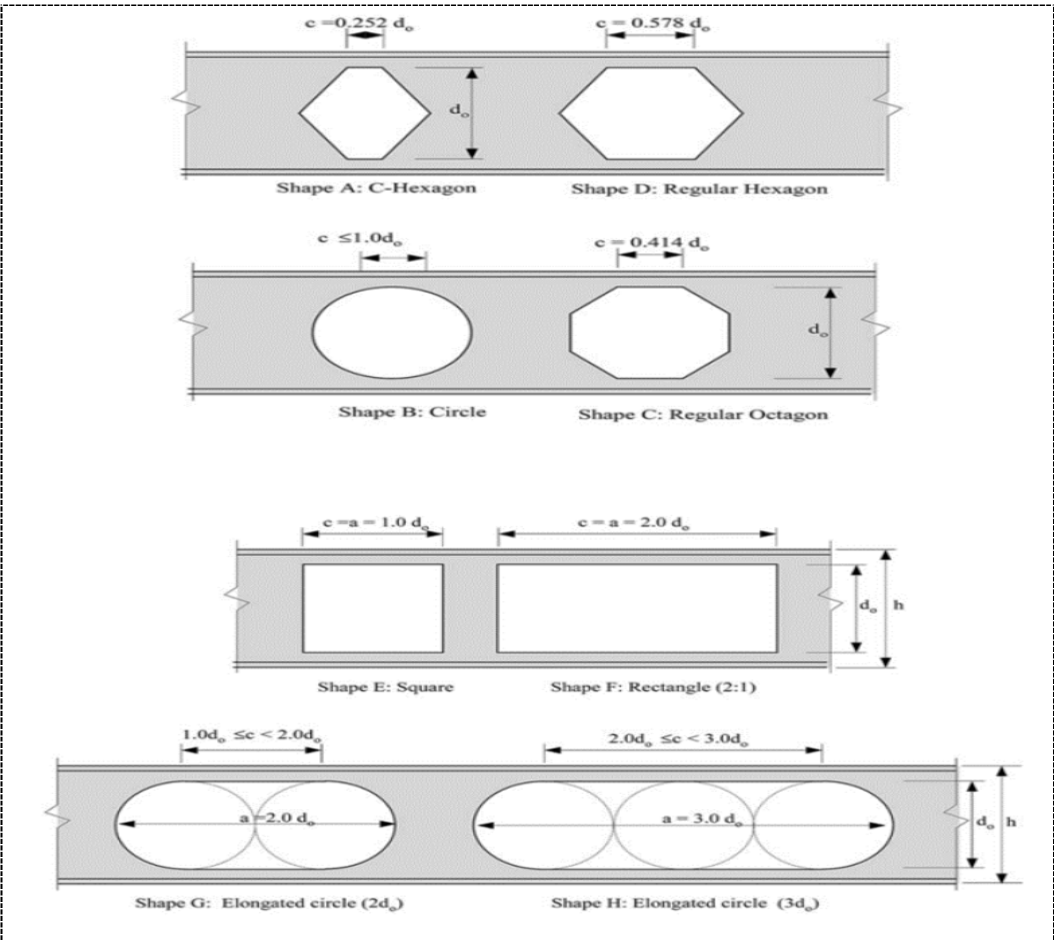

Fig. 3: Steel beam with diverse shapes of web orifices [10].

3. Factors affecting structural behaviour of cellular steel beam

Including web openings in steel structures with I-section beams serves three primary purposes, as outlined by [40]: (i) Allowing for services to be accommodated within the floor-ceiling zone such as ducts, pipes, electric wires, and other utilities. (ii) Reducing material usage while maintaining structural strength and serviceability. (iii) Alleviating high stresses on beam-column joints. Also, the inclusion of multiple openings in the structures serves an architectural function. Conversely, perforated steel beams load-bearing capacity and failure behaviour can be influenced by fluctuations in opening geometry, which will be clarified in this section.

3.1. Opening shape

It greatly affects the overall structural behaviour of cellular beams. This fact has been proven by several studies. In the case of static loading, [10] have discussed the primary structural characteristics of steel beams with large web openings of various shapes and sizes as shown in Figure 3. The study revealed that all studied steel beams experience similar deformation patterns and failure modes when subjected to various moments and shear forces. A numerical investigation carried out by [41] examined the vibration behaviour of steel beams featuring rectangular web openings. The natural frequency showed slight changes when different web opening arrangements were utilized. Nevertheless, it was found circular and elongated web openings undergo crucial Vierendeel behaviour caused by the strong interaction of forces and moments in the axial and shear directions. Moreover, there has been considerable research done on steel beams featuring web openings, utilizing both experimentation and numerical methods. [42-43]. They have revealed that hexagonal and circular openings outperform square and rectangular ones in terms of efficiency.
In the same manner, some researchers have suggested that the shape parameter can influence the distribution of stresses within the beams, which in turn affects their load-carrying capacity and failure modes [44-45]. Similarly, [46] numerically analysed the bearing behaviour of composite beams with different web openings. The key findings show that Circular apertures exhibited the most favourable mechanical performance in terms of stress distribution, with the largest bearing capacity and deformation capacity. However, in the same methodology, [8] concluded that rectangular openings are more crucial than circular due to the formation of high-stress concentrations around the corners. The high-stress level caused the beam to break, leading to a Vierendeel action after the creation of four plastic hinges at the corners.

Through experimentation and analysis, [47] investigated the performance and durability of seven cellular beams with innovative configurations of web openings. One of the conclusions of the study is that the shapes of the openings can also impact the ease and cost of fabrication, which is an important consideration in practical applications. Accordingly, it was also noticed that the manufacturing procedure of non-standard web openings was noted to have advantages compared to the manufacturing of more popular cellular beams.
In the final point, the shape parameter significantly affects the load-carrying capacity as it alters the stress distribution across the web section of the steel beam. in addition, circular shape proves to exhibit the most optimal for structural behaviour in terms of stress distribution. However circular and also circular elongated undergo crucial Vierendeel behaviour caused by the strong interaction of axial and shear forces and moments. However, the corners of rectangular openings are prone to high-stress concentrations, making them more critical than circular openings.
The impact load response of steel structures and their relationship with the initial shape has only been examined in a few studies [9, 11, 48]. Based on their research, the reasons for failure differed significantly depending on the shape of the openings. In addition, it was found that the rectangular openings were extremely vulnerable to damage as their edges showed significant stree levels.
In brief, the openings shape has a significant effect on the behaviour and performance of perforated steel beams, regardless of the applied load. All the previous studies are focused on circular and rectangular but none of them were conducted on elongated openings which are commonly used in engineering fields [47].

3.2. Opening depth

Although the behaviour of steel beams with different web openings may appear similar, the critical opening length and depth should be given special attention during the design and analysis of perforated sections as they significantly impact the overall structural performance. Particularly, the maximum load capacity and rigidity of steel beams can decrease as the openings area increases [49]. Indeed, several studies have supported this which is mentioned in this section.
A thorough examination was carried out by [50] using finite element (FE) techniques to investigate the relationship between shear and moment and determine the failure mode in steel beams with different web openings. Hence, it was found that increasing the openings depth consistently diminishes the shear and moment resistance in perforated sections. They also found that the depth of the opening has a marked influence on the occurrence of shear and flexural failures in perforated sections. [51] obtained identical results by examining the ultimate load-bearing capacity of 21 steel-concrete composite beams incorporating rectangular web openings. According to the study, a larger opening length and height result in a weaker composite beam. The impact of varying opening sizes on the structural behaviour of steel beams was investigated also through a numerical study led by [52]. Findings showed that a deeper opening led to a decrease in load-bearing strength and a heightened probability of initiating Vierendeel action. [53] reached to same conclusions, after investigating seven cellular beams with circular or elongated including solid beams subjected to shear loading. Upon conducting a numerical analysis, [54] determined that deeper circular openings result in greater stress distribution.
Finally, the decrease in the load-bearing ability of the beams, caused by increasing depth of openings, can be attributed to the reduction in the effective cross-sectional area of the steel beam. As a result, four plastic hinges are formed at the opening corners, leading to Vierendeel action.
In terms of impact load conditions, both experimental and analytical limited studies have been carried out. [7] has conducted a comparative study of the behaviour of cellular steel sections under static and dynamic loads (IPE500). Based on the results, it was concluded that the deflection and energy dissipation time are notably affected by the opening depth-to-beam height ratio, with a minor impact on shear force and bending moment within the specified range (0.5-0.7). The effect of impact loads on high-strength steel beams with circular web openings (HSSBCWOs) was thoroughly investigated [55]. The maximum mid-span displacement is greatly influenced by both the impact energy and the height of the opening, according to the results. In addition, [11] created a (FE) model to forecast the impact behaviour of perforated steel beams with circular openings under impact load. Accordingly, the impact responses of steel beams are minimally affected by the depth of the opening, as observed. Moreover, A laboratory study examined the effect of various parameters, which included opening depth, on rectangular openings in web sections [9]. According to the study, altering the depth of an opening in steel beams (to approximately 70% of their total depth) has little impact on their resilience to flexural impact.
In summary, the depth of web openings has a critical role in steel beam performance. On the other hand, the effect is negligible when the opening's depth passes 70 percent of the beam height.

3.3. Spacing between openings (S)

To gain a comprehensive understanding and improve the structural performance of steel beams with web openings, it is crucial to analyse the spacing between these openings. This is supported by a review of previous studies in the following section.
In terms of static loading conditions, countless studies, both experimental and analytical, have been conducted. Seven beams were tested [8]. Five of them had circular web openings, while the other two had rectangular openings with different spacing between them. The study demonstrated that the spacing between openings (S) and the depth of the opening ratio (S/D ratio) have a significant impact on the performance of steel beams. As the S/D ratio increases, both the maximum load-bearing capacity and structural stiffness decrease. Through experimentation in a controlled environment, the effects of

closely spaced web openings on load-carrying capacities, failure modes, and areas of high stress near the web openings were examined [47]. They have also developed a numerical model that can predict local buckling in the web post area for perforated sections with various closely spaced new web opening shapes. It was determined that the spacing between web openings significantly affects the effective strut action of the web-post buckling. The "strut" functions at a 45-degree angle across the member, and its length is determined by the spacing between the web slots. The spacing between web holes greatly affects the effective strut action of perforated steel beams. This in turn affects the strut length and stress distribution near the web openings. A numerical analysis was performed to determine the optimal ratios of (c/c) spacing to opening width and opening depth to section depth for a hybrid steel beam with hexagonal web openings [56]. The results indicated that the ideal spacing to opening width ratio is 1.5 for opening depths less than 60% of the beam depth. Spacing ratios less than 1.5 cause web buckling and prevent access to plastic capacity. However, for opening depths larger than 60% of the beam depth, this results in a notable reduction in load-carrying capacity.

In short, the spacing between holes has a notable effect on the effectiveness and productivity of steel beams. In addition, vulnerability to web post-buckling is directly influenced by (S)

Current studies have focused on investigating the influence of the spacing parameter on the dynamic response of steel girders, as will be discussed in this section. To improve the construction and design of steel buildings, [7] conducted an in-depth analysis of the cellular beam (IPE500) to establish the ideal section. According to the results, the spacing between openings to beam depth (S/H) ratio has little effect on the member deflection. However, it significantly affected the shearing ability. As the S/H ratio increases, there is a decrease in the maximum shear followed by a gradual increase, while the occurrence time decreases steadily [37] conducted multiple drop hammer experiments on steel beams featuring hexagonal web holes (SBHWO). The results revealed that the spacing between holes had a significant impact on the strength, displacement and torsion of the SBHWOs. The study found that larger slot spacing resulted in a decrease in impact duration, web column buckling, and post-impact displacement, while maximum impact strength showed an increase. This means that the overall impact resistance and behaviour of SBHWOs are strongly influenced by the arrangement and spacing of the openings. [55] conduct a comprehensive study on high-strength steel beams (HSSBCWOs) with the response of circular web openings to transverse impact load. Similar to [7], the results revealed that the mid-span displacement of HSSBCWOs is slightly affected by differences in the spacing between slots.

In summary, the spacing of openings significantly affects the dynamic behaviour of steel beams. However, this impact becomes less significant when considering the maximum deflection of the object being impacted.

3.4. Slab thickness

In this section, the impact of RC slab thickness on the performance of composite beams will be explored by reviewed several studies that have demonstrated its significant role in shaping the performance of these structural elements.

Fifteen full-scale tests until failure by [57] have been conducted to provide an in-depth comprehension of the performance of perforated composite beams with ribbed slabs. The results show that increasing slab thickness leads to more frequent slab-steel separation, termed as bridging. To examine the load-bearing behaviour of composite beams with distinct web openings. An analysis was performed on six composite beams with varying opening shapes using the (FE) software ANSYS [46]. It was found that slab thickness has a notable contribution to the shear capacity of the member. Similarly, [58] conclude that after experimentally examining five continuous composite beams, increasing slab thickness leads to an increase in the load-carrying capacity.

In conclusion, the addition of a slab greatly enhances the load-carrying and shear abilities of a static-loaded composite beam, surpassing those of a bare steel beam.

Regarding studies have addressed the effect of slab thickness on the dynamic behaviour of the composite beam. [59] conducted an investigation on the seismic response of a composite beam-column joint that includes an external annular stiffener. Four samples underwent cyclic stress testing, along with a detailed examination of the interaction between the steel girder and concrete slab. The study's results show that the seismic performance of the connection between a steel beam and a hollow square steel or a concrete-filled square tubular column is significantly affected by the presence of an upper concrete slab. The inclusion of a concrete slab typically led to an increase in the bearing capacities of the specimens. Two steel beam-column joints, one with an RC slab and one without, underwent a series of trials to examine their impact behaviour [34]. Based on the data analysis, it was determined that the behaviour of connections is greatly influenced by both the type of connections and the properties of the slab.

Simply put, having slab results in a positive effect on the structural behaviour of the steel beam, just like it does with static loads. In other words, it enhances the load-carrying capacity, including shear capacity and moment capacity.

3.5. Number of openings

The number of web openings has a significant effect on the behaviour of cellular steel beams and considered as a critical aspect in the structural engineering of members. With an increase in the number of openings, the structural response and load-carrying capacity of the beams may undergo notable changes, impacting their overall performance and safety. These effects will be discussed in this literature.

180 numerical models were used to study the flexural capacities of H-section high-strength steel beams with web openings [60]. Results revealed that the quantity of web openings in H-section high-strength steel beams greatly influences their

bending capacities and the mode of failure. More precisely, an increase in the number reduces the load-carrying capacity and accelerates the failure. [61] reached the same conclusion after examining six I-section beams and conducting a numerical analysis with Abaqus software. Nine simply supported cellular beams were evaluated under concentrated load [53]. The results showed that increasing the number of openings parameter from 2 to 3 resulted in a slight 8.73% decrease in the ultimate load-carrying capacity. According to the authors, this negative effect depends on the size of the openings. In more straightforward terms, enlarging the number and dimensions of openings results in a notable decrease in load-carrying capacity.

In summary, the load-carrying capacity of the steel beam is minimally affected by the number of openings, as indicated in the studies mentioned. However, the magnitude of this effect is determined by the size of openings, making it highly influential.

The effect of the number of openings on dynamic behaviour has been investigated in various studies. [11] conducted both experimental and numerical investigations to assess the dynamic behaviour of steel beams containing circular web openings under impact loading. It was observed that increasing the number of openings from 3 to 7 negligibly decreases the impact force and increases the displacement by 3% and 7.5% respectively. This implies that a rise in the number of openings causes a higher degree of distortion or displacement in the beam under impact forces. In a similar vein [9] came to the same result through their use of a validated (FE) model to analyse the dynamic response of steel beams featuring rectangular openings. According to the authors, a rise in the number of openings leads to a decrease in bending moment and impact load, while also causing an increase in maximum deflection.

Similarly, like in static load conditions, the dynamic behaviour of the steel beam is also adversely affected by the number of openings. This results in a decrease in the load-bearing ability, including shear and moment strength, causing an overabundance of deflection. capacity.

4. Conclusion

One significant contribution of this paper is the exploration of the impact of web openings on the overall performance and behaviour of structural members. The incorporation of web openings in steel beams is a crucial aspect of structural engineering, and this study highlights how factors such as depth, spacing, and shape of web openings can significantly affect the structural behaviour of perforated steel beams under both static and impact conditions. Additionally, the paper discusses the importance of slab thickness in shaping the Dynamic performance of composite beams. The purpose of this review is to explore the dynamic behaviour of cellular beams by reviewing experimental, numerical, and analytical studies. Furthermore, the following conclusions can be deduced from the reviewed papers:

- Incorporating web openings into steel beams has proven to be a feasible method for reducing construction expenses. Nevertheless, this method presents difficulties including reduced stiffness and strength
- The addition of a slab greatly enhances the load-carrying and shear abilities of composite beams under impact load, surpassing those of a bare steel beam.
- The depth and spacing of web openings have been found to significantly impact the structural behaviour of perforated steel beams, while the shape of web openings can influence the distribution of stresses within the beams.
- Few studies have looked at the effects of elongated web openings and slab thickness in composite structures when they experience impact loads, emphasizing the necessity for more research in this field.
- Further research is recommended for fully understanding the dynamic behaviour of these structures and developing innovative techniques to enhance their stiffness without requiring more steel.

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