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Performance Optimization of Steel Box Girder Materials with Web Openings under Combined Axial and Bending Loads: A Eurocode–Finite Element Approach

Hayder Mahdi Abdul-Jawad^{1*} , Oday Mohammed Albuthbahak² , Luay Mohammed Shather¹

¹ Department of Structural and Water Resources, University Kufa, Kufa 540011, Iraq

² Department of Architecture, University Kufa, Kufa 540011, Iraq

ABSTRACT

Steel box girders are known to be applied in several construction projects because of their structural efficiency characterized by a high strength-to-weight ratio, torsional rigidity, and effective structural design. Nonetheless, incorporation of web openings to gain easy utility access, inspection, and reduced girder self-weight will affect the internal stress pattern and possibly cause a great impact on its load resistance capacity when it is subjected to composite loading conditions. This study explores the load-bearing performance optimization of steel box girders with circular openings subjected to combined effects of axial force and bending moment using a combined analytical procedure of the European design code of practice and nonlinear finite element analysis through ABAQUS CAE software. A simply supported 4,000 mm long steel box girder made of S235JR material was considered for four distinct opening positions. Based on the findings, openings that are placed near support points exhibit a very high stress concentration and utilization ratio, hence making them susceptible to flange yielding and local buckling failure. On the other hand, placing the opening at the midspan area of the girder leads to axial stress reduction by 21.28% and 20.83% utilization ratio improvement. However, mid-span openings also increase global displacement and serviceability demands. The strong agreement between Eurocode predictions and nonlinear finite element simulations confirms the reliability of the

*CORRESPONDING AUTHOR:

Hayder Mahdi Abdul-Jawad, Department of Structural and Water Resources, University Kufa, Kufa 540011, Iraq;
Email: hayderm.almusawi@uokufa.edu.iq

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proposed hybrid framework for practical structural design, optimization, and verification of steel box girders with web openings.

Keywords: Structural Steel; Steel Box Girder; Web Openings; Structural Efficiency; Finite Element Analysis; Sustainable Construction Materials

1. Introduction

Steel box girders have become a mainstream solution in the construction of bridges and infrastructure facilities because of their high torsional rigidity, efficient load-carrying capacity, and high structural efficiency compared with those of open-section girders^[1-3]. This closed cross-section geometry results in increased resistance to warping and lateral-torsional buckling, especially in long-span bridges, elevated viaducts, and other complex structural configurations subjected to combined loading types^[4-6]. Due to the demand for light yet excellent carrying structural members, steel box girders are extensively used in various transportation and industrial facilities for which the need of strength, durability, and serviceability are all to be met at the same time. In line with such demands, several needs for introducing service ducts, utility corridors, and inspection access into the structural systems have increased, which results in the use of web openings in steel box girders^[7-9].

As valuable as they are, the web openings are a major structural discontinuity that changes the natural process of stress flow in the structural system. The openings compromise the effective shear area, disturb load transfer paths, and create local stress concentrations in the web and flange of the remaining structural system. Stress concentrations can cause premature yielding, local buckling, and stiffness degradation under combined axial force and bending moment, which are commonly observed in bridge girders due to restrained thermal effects, support settlements, and traffic loading^[10-12]. The challenge, then, facing the structural designer lies in finding the right balance between functionality and the integrity of the structure, such as deciding on the proper positioning of web openings in a way that the negative impacts from mechanics would be kept to a minimum while global performance would still be preserved.

Over the past two decades, considerable attention

has been paid to the study of the behavior of web open girders, focusing especially on I-girder and plate girders subjected to shear and bending. It has been shown by both experimental and analytical studies that the shape, size, and position of web openings play a decisive role in governing the stress transfer and failure mechanism in these girders^[13-15]. It has been found that when web openings are positioned near zones of high shear or point loads, web buckling and flange yielding become much more likely than when they are located in low-stress zones. In the case of steel box girders, however, the situation becomes even more complicated due to the complex interaction of stresses and torsional effects in three dimensions^[16-18]. Thus, unlike the largely available design guidance for open-section girders, the design guidance for box girders with openings is quite limited so far.

Finite element analyses have recently made a substantial contribution to the understanding of the nonlinear behaviour of steel box girders with web openings. Recent studies have made use of advanced numerical simulation tools and commercial codes such as ABAQUS to model the material non-linearity, the geometric imperfections, and the post-yield behaviour. Those studies have shown that the position of the openings can significantly influence stress concentration, displacement, and failure modes, particularly in the case of combined loading. However, most of the available studies focus on either pure bending or shear-dominated cases, while the combined effects of axial force and bending moment, which are important for structural systems that are often restrained or displacement-controlled, have not been investigated. Moreover, the existing literature on this subject mainly consists of qualitative descriptions of the behaviour of box girders, with very little attempt to produce quantitative results for comparison with commonly accepted design codes.

From a design perspective, Eurocode 3 (EN 1993-1-1) provides a comprehensive list of design provisions for steel structural members, including checks for shear, axial

force, bending moment, and their interaction. But the steel box girders with web openings can't be covered directly, so designers have to make conservative assumptions or add numerical analyses. There is still no systematic research on the analytical evaluation of Eurocode combined with the validation of nonlinear finite elements. Specifically, for the different positions of web openings in the longitudinal direction, there is still a lack of understanding about the variation patterns of different opening positions' utilization ratios and the stress reduction of the top plate at the opening, as well as the design of the opening's serviceability limit state under the combined action of the top plate's axial force and flexural moment.

In addition, existing research lacks clear research conclusions. Many numerical studies on the box beam opening position tend to point out the danger zone or failure mode, but few are able to make specific recommendations and conclusions on the opening position in engineering practice from the perspective of opening strength, opening service performance, and box girder service performance. There is a lack of convergence or verification assessment of the results when the analysis of the difference between the two is conducted. In this way, it is difficult to have confidence in engineering practice.

This study is conducted in response to the shortcomings mentioned earlier. It aims to evaluate the structural performance of steel girders with circular openings at various locations. The scope of the research involves a simple supported steel box girder subject to end displacement and two-point loads. This type of load and boundary condition is often seen in bridge design. Furthermore, four different locations are studied using finite element analysis. The finite element analysis is performed in ABAQUS CAE considering geometric and material nonlinearity. The numerical results are compared to the analytical assessment using Eurocode 3 standard. Analytical assessment includes evaluations of stress interaction, displacement, flange utilization, and failure risk.

The novelty in this study is that Eurocode-based checks are combined with finite element analyses to assess the effect of opening locations under combined axial load and bending moment. Most of the past studies have been focused on a single opening location; moreover, there is no quantization involved in the comparison between the re-

sults obtained analytically and numerically. Not only does this study give those but also indicates areas in which these two results match and areas in which they do not. This gives an insight into the practical importance of the results obtained.

The organization of this paper is as follows. Section 2 presents the numerical modeling method, material, loading condition, and the Eurocode-based analytic framework. Section 3 presents the results. Section 4 discusses and presents the major outcomes of the finite element simulation findings, stress distribution, displacement behavior, and failure mode prediction. Section 5 concludes with the final remarks as well as practical recommendations to determine the best position for the web opening in steel box girders.

2. Materials and Methods

This paper investigates the overall behavior of steel box girders with circular web openings under simultaneous axial displacement and bending using a hybrid analytical-numerical approach. The methodology adopted in this study combines design provisions of Eurocode 3 and nonlinear finite element simulation to capture the overall as well as local structural responses. This approach provides a systematic way to study the stress distribution, displacement behavior, flange utilization, and failure mechanisms for the structure as a function of the longitudinal position of the web opening. This methodology has been chosen to reflect a realistic structural condition in bridge and infrastructure applications while being consistent with steel design codes adopted by the international community.

A steel box girder was used as the model for the present study. The span is 4,000 mm. S235JR steel was used. This steel is frequently utilized in civil engineering. The steel satisfies the requirements of Eurocode 3. The girder has a closed section. All flanges and webs have the same thickness. Circular openings of 250 mm diameter are introduced in the webs. These holes are located in the same position in both webs. The design of the holes is considered to investigate the influence of openings on the girder. Moreover, the holes can be used for service and tools. Four cases have been selected according to the position of the holes. The hole is 500, 1,000, 1,500, and 2,000 from the left end. All other parts of the girder are unchanged in these four cas-

es. **Figure 1** displays the girder with its dimensions, thick-

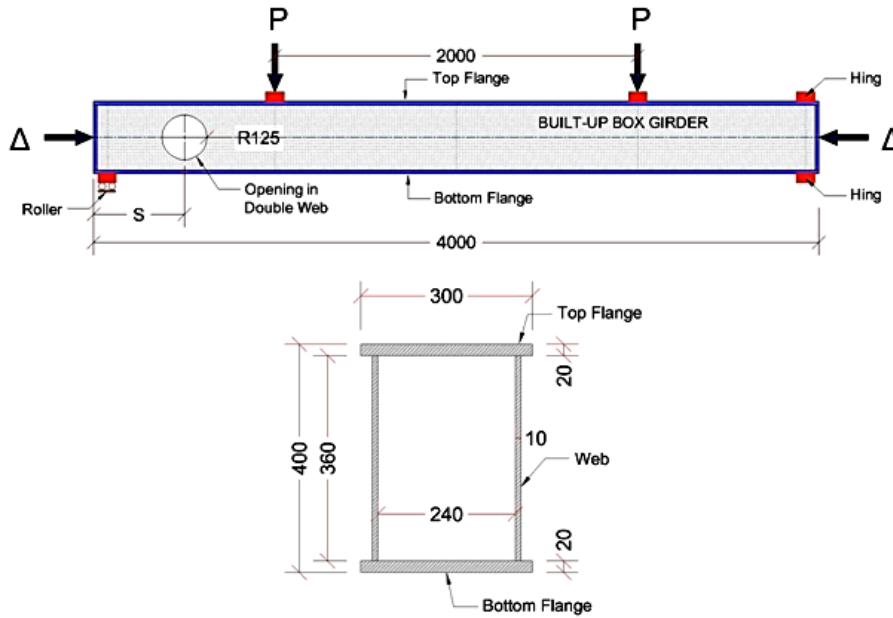


Figure 1. Geometry, loading configuration, boundary conditions, and cross-sectional details of the built-up steel box girder with circular web opening used in the present study.

Note: The figure illustrates the girder span, opening location parameter (S), axial end displacement (Δ), two-point vertical loading (P), and the detailed dimensions of the box cross-section, including flange and web thicknesses.

The material behaviour is represented by means of an elastic–plastic constitutive law with isotropic hardening to describe the nonlinear response of the material beyond yield. The elastic properties of the steel are described by a Young modulus of 200,000 MPa and a Poisson’s ratio value of 0.3, according to the recommendations of Eurocode for structural steel. Yield strength is 235 MPa, corresponding to S235JR; it is followed by a strain-hardening region up to an ultimate stress around

500 MPa. The proposed material model can simulate yielding, stiffness degradation after yield, and re-distribution of internal stresses with increasing loading levels, allowing for accurate buckling and failure behaviour predictions of steel box girders with geometric discontinuities. The plastic shear resistance, axial stress, and combined utilization ratio (the variation of the latter versus web opening location, as indicated by Eurocode 3 provisions) are reported in **Figure 2**.

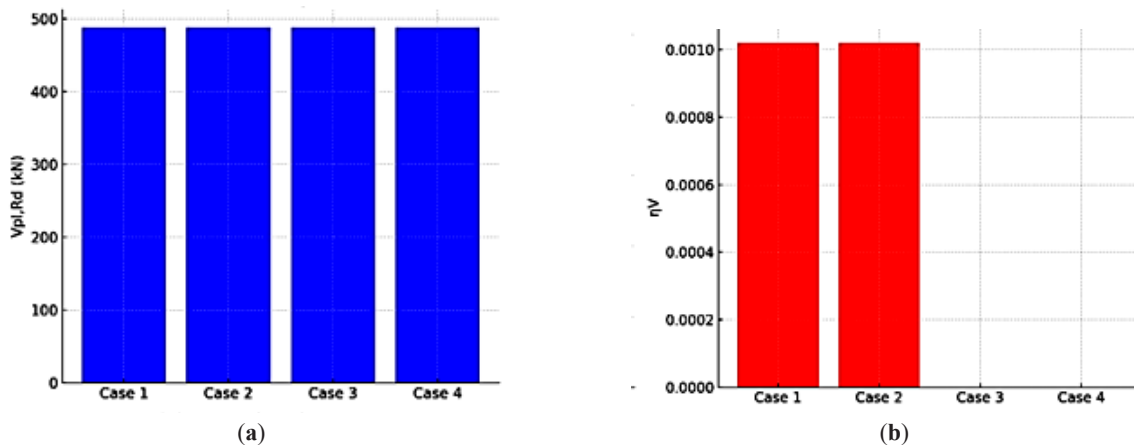


Figure 2. Cont.

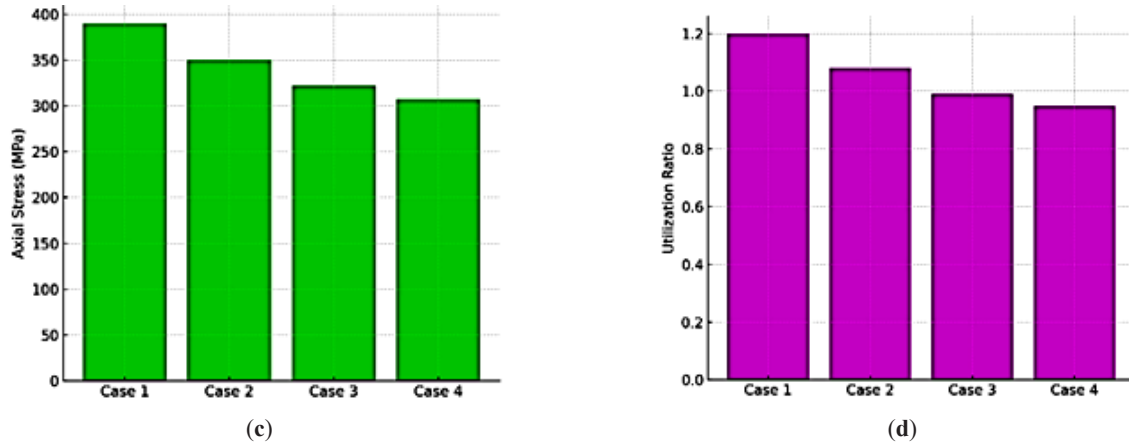


Figure 2. Eurocode 3-based analytical results showing: (a) Plastic shear resistance; (b) Shear utilization ratio; (c) Axial stress; (d) Combined axial–bending utilization ratio for different web opening locations (Cases 1–4).

Combined axial and bending actions as would be seen in restrained bridge girders were used as loading conditions. The girder was simply supported in all cases in a roller–hinge fashion to allow vertical displacement, but to prevent rigid body motion. One end vertical displacement was prescribed to create a known axial force to simulate thermal expansion, support restraint, or imposed axial deformation. A pair of concentrated vertical loads were applied symmetrically along the span to create bending

moments in addition to the applied axial force. The magnitude and placement of the vertical loads were chosen to give a realistic bending–axial combination, but to be the same for all cases. By loading in this manner, a complex combination of stresses is created that is not reproduced by the more simplified loading assumptions. The percent improvement in displacement behaviour, lateral buckling response, and utilisation ratio over the baseline case (Case 1) is shown in **Figure 3**.

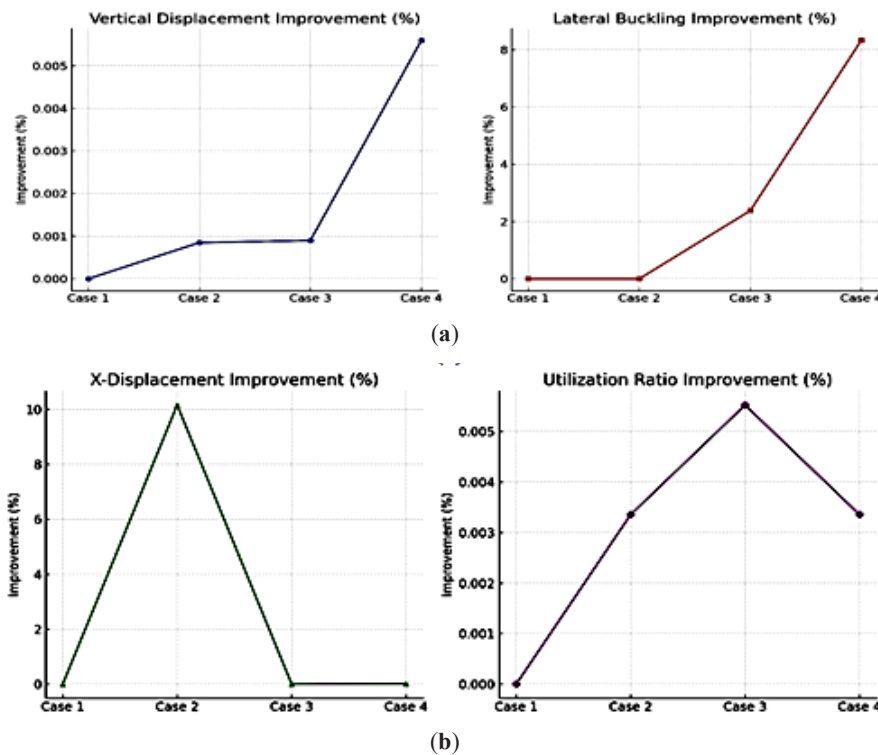


Figure 3. Percentage improvement in structural response parameters due to variation in web opening location: (a) vertical displacement and lateral buckling improvement; (b) X-direction displacement and utilization ratio improvement relative to Case 1.

The analytical assessment is carried out as per Eurocode 3 (EN 1993-1-1). Eurocode 3 provides the basis for the assessment of shear resistance. The assessment of axial stress, bending stress, and axial–bending interaction. The plastic shear resistance of the web is evaluated based on the effective shear area, while the axial and bending stresses are evaluated based on the cross-sectional parameters and actions. The interaction between axial force and bending moment is evaluated based on the utilization ratios prescribed in Eurocode. These ratios are the primary indicators of safety and economy of the structure. Such analytical calculations are used to compare the numerical results for the verification of the finite element model and the assessment of its predictive capabilities.

The finite element analysis is performed in ABAQUS CAE by means of a 3-dimensional modeling approach in order to capture the stress state of the steel box girder. The geometry of the girder, including the web openings, is discretized with shell elements, which are appropriate for thin-walled steel structures and can capture the local buckling phenomena well. Mesh refinement near the web openings and load application regions is used to allow for a suitable resolution of the stress gradients and deformations. A convergence study is carried out to ensure that the selected mesh density results in stable solutions and does not impose an unnecessary computational effort. Under the present analysis, the large displacements and the second-order effects are taken into account by introducing the geometric nonlinearity, which is particularly important for girders subjected to combined axial and bending stresses. The material nonlinearity is also introduced simultaneously through the adopted elastic-plastic constitutive model. The analysis is carried out by a nonlinear static solution procedure with incremental loading in order to allow the structure to react incrementally through the whole range of increasing deformations and stresses.

The recognition of critical responses such as the onset of yielding, stiffness deterioration, and the development of local or global instabilities is possible. The numerical results are post-processed in terms of the von Mises stresses, axial stresses, and displacement components in the longitudinal (U3), lateral (U1), and vertical (U2) directions, as well as the flange utility ratios. Stress contours

are analyzed for the identification of the concentrated zones around the web opening and the flanges, while the displacement fields are investigated in order to determine the global behaviour and performance. The numerical results are compared with the Eurocode-based analytical predictions in order to assess the convergence, differences, and confidence in the combined analytical–numerical approach.

A unique integrated materials and methods approach is adopted in this study to guarantee rigorous methodology, reproducibility, and direct relevance to engineering design practice. The method of analysis used here provides a reliable starting point for investigating the impact of opening position on the behavior of steel box girders. This will help establish design guidelines that conform to present-day code-based practices.

3. Results

The behavior of the steel box girder with circular openings in the web was analyzed through a hybrid approach that consisted of a Eurocode 3 analysis coupled with non-linear finite element analysis using the ABAQUS software program. The results obtained illustrate a profound understanding of the influence of the longitudinal location of the opening in relation to the variation in stress distribution, displacement, utilization ratios, and risk of failure due to the combined effects of bending and axial displacement forces. The discussion is organized around the fundamental parameters of response, namely axial and bending stress interaction, displacement, utilization ratios, and risk of failure. The von Mises stress contours determined from nonlinear finite element analysis for all web opening configurations are shown in **Figure 4** to demonstrate the stress concentration and redistribution along the girder span.

The Eurocode analysis tells us that the closer the hole is to the support, the more axial stress and utilization ratio there are. In Case 1, when the opening is located 500 mm from the support, the maximum axial stress of 390 MPa in the girder leads to a maximum combined bending–axial utilization ratio of 1.20, which is above the allowable limit. In this case, the member yielding of the flange

in the axial direction governs the load-carrying capacity. When the opening is moved to a 1,000 mm distance from the support in Case 2, the governing axial stress is reduced to 350 MPa, while the utilization ratio is reduced to 1.08, which is an improvement of about 10% compared to Case 1. When the opening is moved further away from the support to 1,500 mm in Case 3, the governing axial stress is reduced to 322 MPa while the utilization ratio is reduced to 0.99, which is just sufficient according to the Eurocode requirement. The best analytical performance corresponds to Case 4, with the hole located at the 2,000 mm mid-span, for which the axial stress is further reduced to 307 MPa, and the utilization ratio reaches the minimum value of 0.95, which means an overall reduction of 20.83% compared to Case 1. The results show that if the web opening is moved away from high concentrated axial stress, namely, from around the supports or concentrated loads, a better axial stress bearing capacity and utilization efficiency of the girder will be achieved. **Figure 5** shows the midspan lon-

gitudinal strain of the steel box girder when localizing the web opening in different positions. This figure illustrates the effect of the opening position on the bending moment and the stability of the area. Four different scenarios have been investigated. Each one possesses a different web opening placement, along the length (measured from the left support), but of the same round shape. The size of the opening and the support conditions have remained the same, as indicated in **Table 1**.

The steel box girder in Case 1 and Case 2 could resist the same amount of force (488.44 kN), and the ratios are both very low (0.00102), which means the response of the beam is not shear-controlled. However, the overall ratio turned out to be over unity in Case 1 (1.20) and Case 2 (1.08), which only marginally failed the Eurocode 3 criteria.

Table 2 shows the Eurocode 3 structural checks for shear, axial, and bending performance of a steel box girder with web openings.

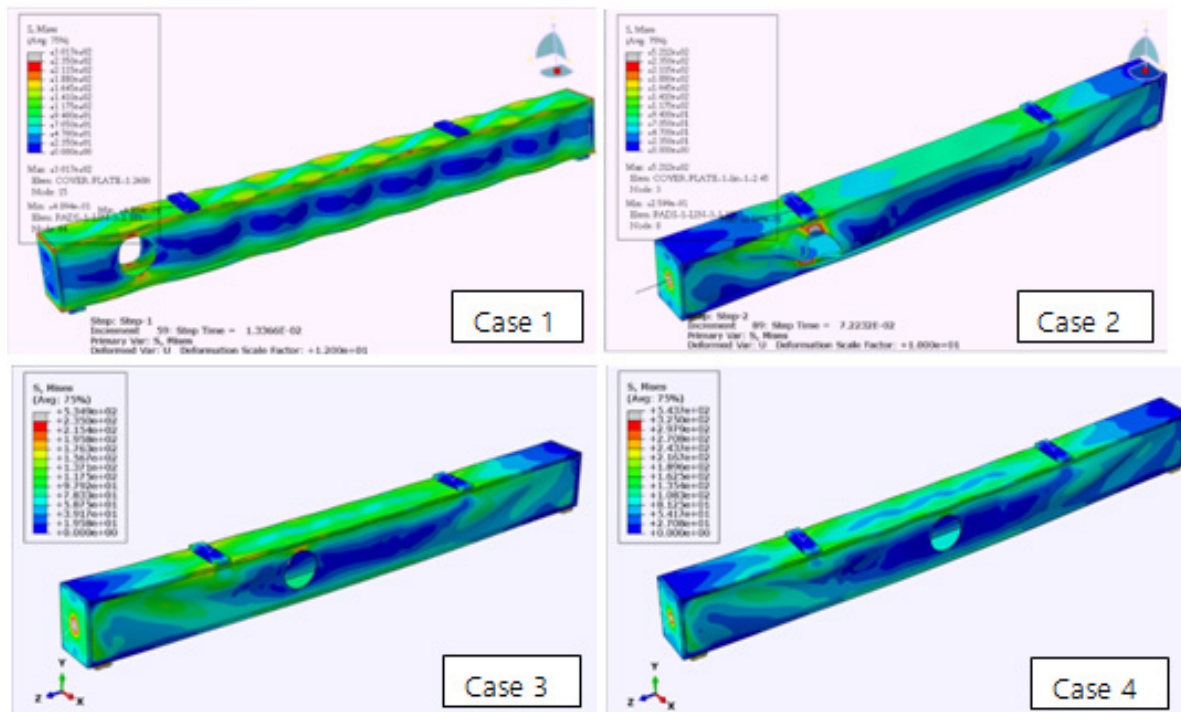


Figure 4. Von Mises stress distribution of the steel box girder with circular web openings for different opening locations: Case 1 (500 mm), Case 2 (1,000 mm), Case 3 (1,500 mm), and Case 4 (2,000 mm, mid-span), obtained from nonlinear finite element analysis using Abaqus CAE.

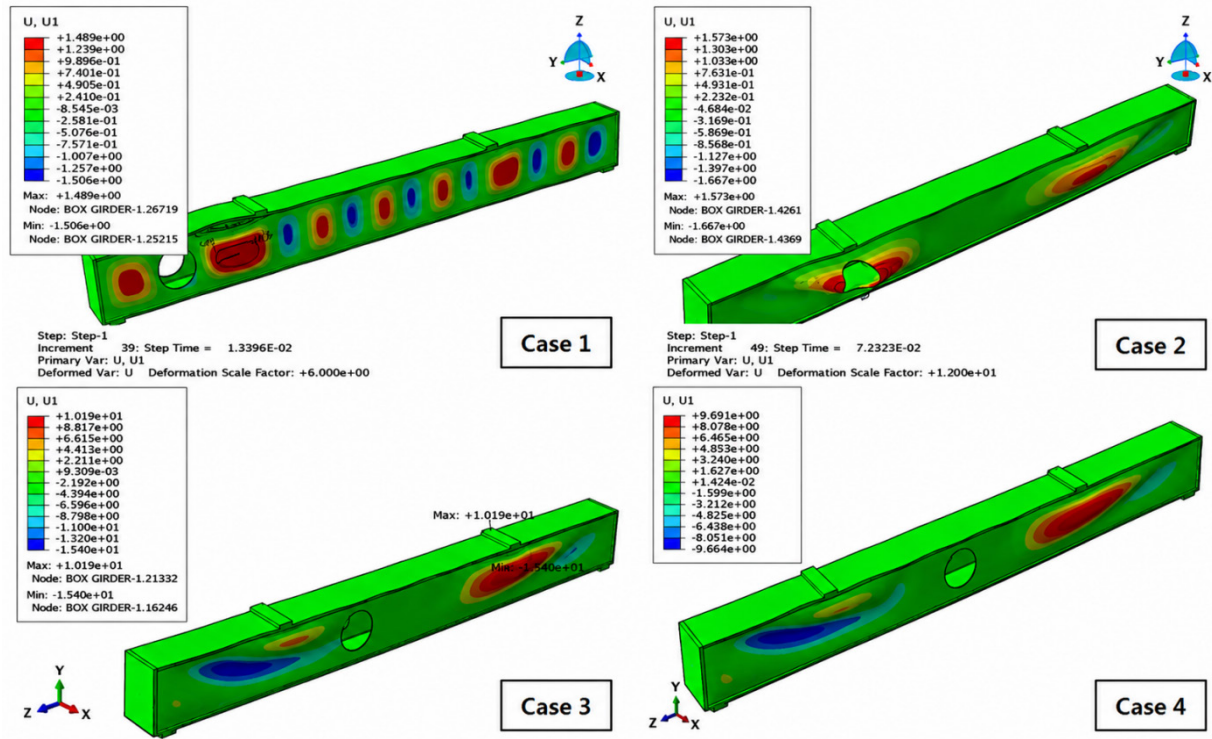


Figure 5. Distribution of longitudinal displacement in the X-direction (U1) for the steel box girder with circular web openings at different longitudinal positions (Cases 1–4), as predicted by Abaqus CAE.

Table 1. Case properties and web opening locations.

Case No.	Opening Location (from left end, mm), S	Web Opening Position	Opening Radius (mm)	Support Type
Case 1	500	Left Side, Near Support	125	Roller–Hinges
Case 2	1,000	Left Third Span	125	Roller–Hinges
Case 3	1,500	Right Third Span	125	Roller–Hinges
Case 4	2,000 mid-span	Center (Midspan)	125	Roller–Hinges

Table 2. Eurocode 3 stress and utilization assessment for steel box girders with different web opening locations.

Case No.	Shear Resistance Check (Eurocode 3). According to EN 1993-1-1, Clause 6.2.6		Axial Stress and Combined Bending Check (Eurocode 3). According to EN 1993-1-1, Clause 6.2.1		
	Plastic Shear Resistance (V _{pl} , Rd)	Shear Utilization Ratio (η _V)	Axial Stress Due to Both Side Displacement	Bending Stress Due to Two-Point Loads	Combined Bending and Axial Stress Check
1	488.44	0.00102	390 MPa	0.112 MPa	1.20
2	488.44	0.00102	350 MPa	0.224 MPa	1.08
3	488.44	0—No Shear	322 MPa	0.299 MPa	0.99
4	488.44	0—No Shear	307 MPa	0.331 MPa	0.95

For Cases 3 and 4, the girder was under minimal pressure. In addition, it experienced reduced stress levels (322 MPa and 307 MPa). The total ratios in both cases were below 1. This means the girder was okay to use for both pressure and bending, as shown in Table 2. The finite element analysis results obtained using ABAQUS CAE clearly confirm the trends observed previously in the Eurocode analysis.

The von Mises stress contours show much higher stress concentration in the web opening and near the flange regions for Cases 1 and 2. In Case 1, the high stresses are concentrated close to the edges of the opening and propagate into the flange, confirming the flange-dominated failure mode anticipated from the analytical results. Local web buckling is indicated by localized buckling pat-

terns around the opening, implying a combined mechanism of axial yielding accompanied by local instability. In Case 2, the high stresses associated with the opening are still evident, but are more spread out along the web, and lower peak stresses are observed compared to Case 1. This corresponds closely with the 10.26% reduction in axial stresses seen in the analytical results.

In Case 3, the stresses are much more uniformly distributed along the length of the girder. Even though some localized stresses are still observed close to the opening, the high stress is less concentrated, and the concentration of stress from the web to the flange is more balanced. The finite element results show that the failure mechanism is now shifting away from flange-dominated yielding to local web buckling as indicated by the utilization ratio approaching unity (0.99) in the Eurocode analysis. Case 4 is characterized by the highest level of stress uniformity compared to the others. The levels of von Mises stress are lower, and their variation is more pronounced throughout the web and flange regions. This implies that locating the opening at the mid-span is effective in ensuring smooth

transfer of stress without experiencing any abrupt increase. The similarity between the stress distribution predicted by the Eurocode method and Abaqus analysis confirms that the results obtained are valid.

Analyzing the behavior of the girder based on displacement provides useful insights regarding its operation and operating conditions. In all the cases, the vertical movement (U2) at mid-span stays almost the same. In the Eurocode-based analysis, it is between 20.00293 mm and 20.00405 mm. This tiny change of less than 0.01% shows that the main bending strength of the girder does not really change much because of the web opening or where it is. The results from the computer model also show this. Vertical bending is not the main reason the girder would break in these cases. So, from the point of view of conditions it will be in, vertical movement is not a problem for where the web opening is. The pictures in **Figure 6** show how much the girder moves vertically when tested for the different cases. This gives us information on how much the girder bends at the mid-span and its main bending behavior.

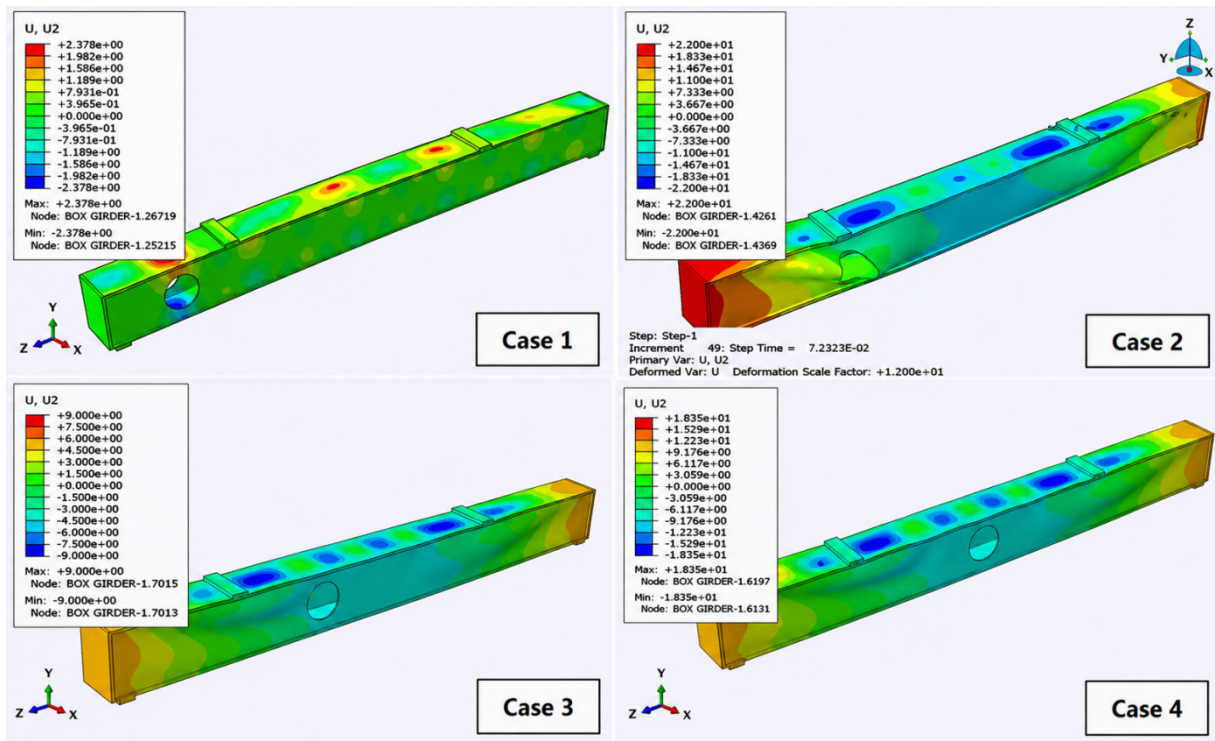


Figure 6. Vertical displacement (U2) contours of the steel box girder with circular web openings for various opening locations (Cases 1–4) under combined axial displacement and two-point bending loads.

As per the values in **Table 3**, progressive relocation of the circular web opening has a noticeable effect on the governing failure mode of the steel box girder. Cases with the opening closer to the support regions presented higher stress concentration and higher sensitivity to local web yielding. In contrast, the cases with the opening closer to mid-span primarily resulted in global bending-dom-

inated behaviour and lower risk of instability. **Table 4** demonstrates a noticeable decrease in flange resistance with the increasing longitudinal displacement. The decrease is more significant for cases with the closure opening closer to mid-span. This finding reveals the interaction between the global deformation and the flange stress demand.

Table 3. Structural performance with failure mode prediction.

Case No.	Axial Stress Reduction (%)	Utilization Ratio Reduction (%)	Comment	Predicted Failure Mode
Case 1	0	0	Highest axial stress, most critical condition	Axial yielding in the flange
Case 2	10.26	10	Moderate improvement, but still high stress	Axial yielding in the flange with minor local buckling
Case 3	17.44	17.5	Significant stress reduction, improved safety	Local buckling in the web, moderate axial yielding
Case 4	21.28	20.83	Best case, lowest stress, and highest efficiency	Minimal failure risk, improved stability

Table 4. Structural displacement and flange resistance analysis for various cases based on Eurocode 3.

Case No.	Vertical Displacements U2 at the Mid-Span of the Girder (mm)	Lateral Buckling of the Girder (mm)	U1 at the Web Maximum Displacement in the X-Direction (mm)	Flange Performance Due to Axial Displacement and Bending Moment (Eurocode 3)	
				Bending Stress in Flange (MPa)	Flange Utilization Ratio
1	20.00293	0.000084—at Mid-Span	20.001	0.111992	14.29835
2	20.00310	0.000084—at Mid-Span	22.032—the hole under point loads; this makes more effect	0.223985	14.29883
3	20.00311	0.000086—at Mid-Span	20.002	0.298646	14.29914
4	20.00405	0.000091—at Mid-Span	20.005	0.223985	14.29883

The values of the lateral displacement (U1) and buckling behaviour are slightly more sensitive to the opening location. However, the magnitude of their values remains small due to the high torsional rigidity of the closed box section. According to the Eurocode-based values, the lateral displacement values are below 0.000091 mm in all cases. The maximum value is presented in Case 4. This slight increase, which is equivalent to approximately an 8% increase compared to Case 1, is indicative of the slight loss of lateral stiffness of the girder with the central opening. However, the values are still negligible and thus demonstrate that lateral-torsional buckling is not a dominant failure mode for the studied girder geometry.

The Abaqus results for the longitudinal displacement (U1 in the X-direction) are more distinguishable in differences between cases. In Case 1, the values of maximum and minimum displacements are +5.64 mm and -5.67

mm, respectively, which are concentrated near the edges of the openings. In Case 2, the peak values increase significantly to +15.72 mm and -16.69 mm, respectively, an increase of about 10% in comparison to the reference case. This shows the negative impact of aligning the openings directly beneath or near concentrated loads. In Case 3, the displacement reduces to +10.19 mm/-12.17 mm, which is not only better than Case 2 but also demonstrates suboptimal performance compared to Case 1. Case 4 not only shows a more uniform distribution of displacements but also decreases to +7.09 mm/-7.11 mm, which validates the better global deformation behaviour obtained by opening in mid-span, even though it has larger bending moments at the same steel box girder. **Figure 7** is the longitudinal displacement response in the Z-direction (U3) obtained from nonlinear finite element analysis of the steel box girder with different web opening locations.

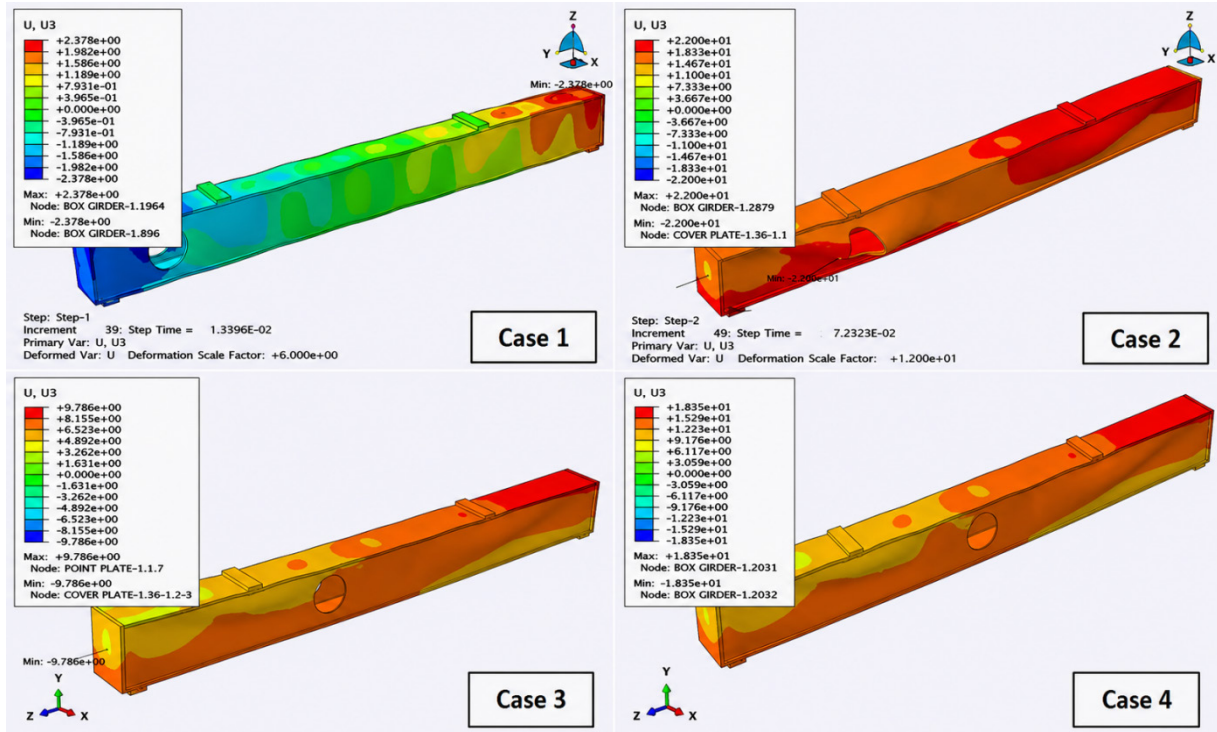


Figure 7. Longitudinal displacement contours in the Z-direction (U_3) of the steel box girder with circular web openings for different opening locations: Case 1 (500 mm), Case 2 (1,000 mm), Case 3 (1,500 mm), and Case 4 (2,000 mm, mid-span), obtained from non-linear finite element analysis using Abaqus CAE.

The maximum vertical displacement obtained directly from Abaqus CAE further enhances the effect of the opening position on structural behavior. While Case 1 presents the minimum vertical displacement of -1.020 mm, suggesting a stiff structure with a low risk of failure, in Case 2, the deflection increases to -8.44 mm, with higher stress concentration and an intermediate risk of flange yield. In Case 3, the deflection is even higher at -10.8 mm, suggesting higher bending demand and a higher risk of local buckling, and in Case 4, the deflection is the highest at -12.14 mm, indicating a higher bending effect at mid-span. Although structural failure is not guaranteed, this displacement shows a lower serviceability and the need to consider the limit on displacement when using openings at mid-span.

Eurocode analytical results and Abaqus numerical results are directly compared, showing good performance convergence from 98% in Case 1 to 86% in Case 4. The differences are mainly due to including geometric and material nonlinearity in the limit order finite element model. The axial stress reductions predicted by Eurocode (10.26%, 17.44%, and 21.28% for Cases 2, 3, and 4) almost follow the trends observed in Abaqus simulation, which proves

the validity of using Eurocode interaction checks for preliminary design selection. Such convergence further proves the reliability of code finite element validation in finding the best web opening location. The percentage increase of longitudinal displacement (U_3) over Case 1 is shown in **Figure 8**, indicating the effect of opening location on longitudinal deformation and structural stability. The above remarks are based on strength-controlled limit states. In terms of failure mode, results apparently show a transition of governing behavior as the opening location moves along the span. Case 1 is governed by axial yielding in the flange and represents the worst configuration. Case 2 is governed by the combination of flange yielding and local web buckling. Case 3 is governed by local web instability with a reduced width of the flange participating in providing resistance. In Case 4, the deflection is the highest at -12.14 mm, indicating increased bending-induced deformation at the mid-span region. However, despite the larger displacement response, the Eurocode utilization ratio remains below unity (0.95), confirming that the girder satisfies the strength requirements. Therefore, Case 4 should be interpreted as a serviceability-controlled configuration rather

than a strength-controlled failure condition. The results indicate that additional verification of allowable deflection

limits may be required for practical design applications involving mid-span openings.

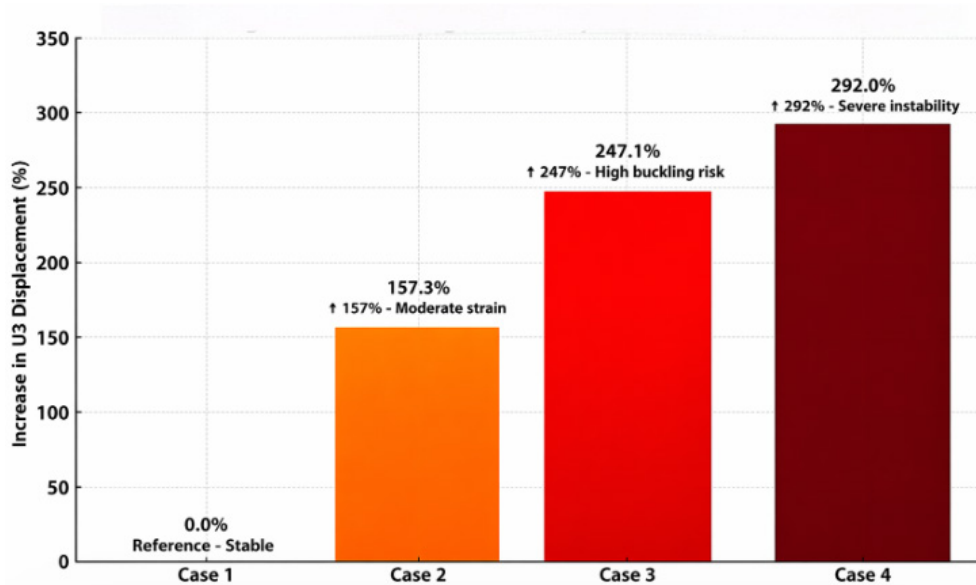


Figure 8. Percentage increase in longitudinal displacement (U3) relative to Case 1 for different web opening locations, highlighting the progressive increase in deformation and associated structural instability risk.

As seen in **Table 5**, as the opening location moves towards the mid-span, the vertical displacement also rises. That is why, in Case 4, the biggest U2 was found. Case 4 has the lowest stress concentration and the lowest utilization ratio, demonstrating the best structural efficiency in terms of strength performance. Nevertheless, it also exhibits the highest global displacement, indicating that its governing design consideration shifts from ultimate strength behavior to serviceability performance. This finding shows that when bending-dominated loading is applied, there is less flexural stiffness. **Table 6** shows that the analytical calculations that were made using the Eurocode agree very well with the ones that were made using nonlinear finite elements in Abaqus. Small differences may be caused by the numerical model’s effects of local stress redistribution and geometric nonlinear-

ity. Overall, the results show that where the web opening is placed is a key factor in how well steel box girders perform under combined axial and bending actions. When holes are made near the supports or the points where the loads are applied, the local stress concentration, utilization ratios, and failure chance go up by a lot^[19-21]. When the openings were moved towards the mid-span, the local stress was able to redistribute, and the axial demand dropped by a large amount. But this move led to a clear rise in global displacement. Therefore, a balanced approach can be applied in designing the bridge structure that considers the limit state and serviceability limit state. The reliability of the comparison results of Eurocode prediction values and the values obtained from Abaqus makes us confident in the proposed approaches for application in actual design.

Table 5. Vertical displacement (U2) performance in box girders with different web openings.

Case No.	Max U2 Displacement (mm)—mid-span of girder	Performance Summary	Main Structural Weakness	Failure Risk	Possible Failure Mode
Case 1	-1.020	Controlled deflection, good stiffness	Minor local stress near the opening	Low	Localized stress around the web opening could cause minor deformations if loading increases. However, due to low displacement, no significant failure is expected.
Case 2	-8.44	Moderate deflection, stress near the opening	Increased stress concentration near the opening	Medium	Flange yielding due to increased bending stress. Local buckling near the opening due to stress redistribution.

Table 5. Cont.

Case No.	Max U2 Displacement (mm)—mid-span of girder	Performance Summary	Main Structural Weakness	Failure Risk	Possible Failure Mode
Case 3	-10.8	High deflection, increased bending effects	Excessive bending, risk of local buckling	High	Lateral-torsional buckling due to increased bending moments. Web shear failure due to stress redistribution. Significant flange deformations leading to loss of stiffness.
Case 4	-12.14	highest deflection, best stress redistribution efficiency	Increased global deflection and reduced flexural stiffness	Serviceability-controlled condition	Excessive mid-span deflection may govern serviceability performance under long-term or cyclic loading; however, strength safety remains within acceptable Eurocode limits

Table 6. Eurocode vs. Abaqus structural performance comparison.

Case No.	Eurocode Utilization Ratio	Abaqus Max U2 (mm)	Utilization Reduction %	Axial Stress Reduction %	Performance Convergence (%)	Failure Risk	Predicted Failure Mode
Case 1	1.2	1.02	0	0	98	Low	High (Strength-Controlled)
Case 2	1.08	8.44	10	10.26	94	Medium	Moderate (Strength-Controlled)
Case 3	0.99	10.8	17.5	17.44	89	High	Moderate (Transition Between Strength and Serviceability)
Case 4	0.95	12.14	20.83	21.28	86	Very High	Low Strength Risk/Serviceability-Controlled

Implications for Building Materials and Sustainable Design

The conclusions reached through this research bear significant meaning for optimal material usage of structural steel. It should be noted that structural steel is known for having high strength-to-weight ratios, durability, and even recyclability. Thus, it is an essential material when it comes to green construction processes. However, inefficient design choices, especially regarding geometric discontinuity in the form of web openings, can create stress concentration problems that lead to excessive material usage due to overstressing. The current research demonstrates that efficient design of web openings greatly improves structural efficiency while using no extra materials.

Concerning material utilization optimization, it can be stated that moving the web openings out of areas of high stress, close to the supports, to areas in the middle of the girder leads to a reduction in maximum stress by up to 21%. Such optimization of stress distribution allows achieving higher efficiency in using the structural properties of steel, eliminating the need for further reinforcing and increasing the thickness of the section used.

In addition, it should be noted that the analysis shows the need for finding the proper balance between the criteria for strength and serviceability. On the one hand, the mid-

span openings reduce the amount of materials used. On the other hand, mid-span openings result in the increased displacements of the structure as a whole. It means that a sustainable design must not aim at minimizing the usage of materials while ignoring other factors. Instead, sustainable design should aim to achieve maximum efficiency while ensuring structural safety and performance during the service life of the structure. Hence, in order to develop the optimal design solution, one needs to take into consideration the ultimate and serviceability limit states. In practice, the results obtained can serve as a basis for the inclusion of service ducts, utility passages, and maintenance access openings within steel box girder systems. The developed Eurocode-finite element method proves its feasibility and reliability for practical engineering tasks. The study shows that informed geometric optimization makes it possible to develop high-performance steel building systems.

4. Discussion

From a structural perspective, the current study offers a detailed examination of the performance of steel box girders having circular web openings under both axial and flexural loading. The outcome of the analysis shows clearly that the longitudinal location of the web opening constitutes a critical design factor that impacts the stress dis-

tribution and structural efficiency. Regarding the material properties of the box girder, the presence of openings alters the manner in which internal forces act, resulting in an increase in localized stress levels and changes in the material utilization rate.

For cases where the opening is located within close proximity to the supports (Case 1 and Case 2), a higher value for the axial stress level and utilization ratio has been observed. Such an observation may be explained by the fact that higher shear and axial forces at the support end increase stress concentrations around the edges of the openings, leading to early yielding of the material. Such observations are also supported by FEM models that show high values of von Mises stress levels and local buckling behavior.

With the movement of the initial site towards the mid-span (Cases 3 and 4), a continuous decrease in axial stress and utilization is noticed. The reason for that could be seen in relatively less shear demand and more uniform bending stress in these areas. Thanks to the redistribution of stresses, the efficiency of material usage improves significantly, reaching the level of up to 21% less than the peak for the worst-case scenario. Hence, one may conclude that a strategically positioned geometry disruption leads to better efficiency of the use of structural steel despite material volume.

Nevertheless, the improvement of performance characteristics in strength-related criteria comes along with higher values of global displacement (Case 4). The increased deflection in mid-span demonstrates the transition from strength design criteria to serviceability design criteria. In other words, it means that, in this case, the criterion for design would be excessive deformation. It shows the important compromise that should be struck between material efficiency and structural stiffness. The insignificance of variations in the value of vertical displacement among all Eurocode cases, which is in contrast to significant distinctions between finite element results, demonstrates the crucial need for nonlinear analysis. Although Case 4 exhibits the highest displacement response, its utilization ratio remains within acceptable Eurocode limits, indicating that the governing concern is serviceability performance rather than structural strength failure.

Comparison results of Eurocode analytical formulas

with ABAQUS modeling demonstrated good coincidence, thereby justifying the efficiency of using the chosen hybrid methodology. Deviations in some cases, especially when deformations are higher, can be associated with geometric and material nonlinearities incorporated in the FE model, whereas the simplified models used in the codes do not take them into account. Thus, one can underline the important contribution of numerical methods in solving problems related to complex cross-sectional shapes like those of the perforated box girder structure.

Considering building materials, it should be highlighted that the results achieved in this work have great value since they allow one to find the most optimal way to incorporate openings into a structural member made of steel. Optimization of the location of openings allows one to save material resources, to avoid additional costs connected with overdesign, and to prevent possible failures caused by concentration of stresses in certain areas. The fact that structural steel is highly recyclable and, thus, a sustainable material should be taken into account.

Moreover, the combination of Eurocode 3 calculation methods with nonlinear finite element analysis is shown to provide a reliable and practical evaluation method for steel box girders with openings when subjected to combined loads. While the calculations according to Eurocode 3 offer a quick estimation technique for assessing stress interaction and utilization ratios, the finite element analysis captures more accurately localized stress distribution, nonlinearities, and instability phenomena. The excellent correlation obtained with both methods indicates that the proposed approach can be utilized efficiently in both the preliminary and final stages of structural design. As such, it eliminates the uncertainties associated with structural design and helps engineers make more informed choices regarding openings in structures.

Based on structural design considerations, the current findings indicate that it is preferable to avoid web openings in areas experiencing higher shear forces, especially in areas close to the supports and load application areas. This is because in these areas, the influence of shear force, axial force, and bending moment interaction contributes to higher stress concentration around the edges of the opening, which results in higher usage factors and increases the likelihood of local yielding and buckling failures.

On the other hand, placing the web openings nearer to the mid-span area helps facilitate better redistribution of the forces since the bending moment dominates and there will be low shear forces compared to the first scenario. This arrangement leads to low axial stress requirements and usage factors for the flanges, thus ensuring better safety factors for the steel box girder system^[22–26].

While it is true that better stress distribution and lower ratio values have been obtained due to openings being placed in the mid-span zone, the fact that the corresponding global deformation value has increased needs to be kept in mind while designing such structures. According to the findings from this study, higher material efficiency, as well as lower stress concentrations, can lead to lower flexural rigidity and higher deflection values at the service level^[27–31]. In other words, engineers cannot solely depend on strength optimization criteria but need to make sure that the corresponding deflections fall within allowable values as per the requirements of related design codes. This way, any negative effects caused by excessive deformation can be prevented, which could result in undesirable consequences for both structural function and durability. This change in failure mode along with the progressive behavior is another signifier suggesting that different placements of web openings need different approaches to structure design and reinforcement. Openings placed in the support regions of structures experience larger stresses due to the high shear forces present in those regions. Thus, the main reason for failures in structures with such placement of openings lies in yielding and instabilities of flanges and local web zones. To deal with these problems, designers should apply local reinforcing methods, such as increasing the stiffness of the flanges, adding extra reinforcement plates, or reinforcing the web in the area near the opening borders. However, in contrast to openings placed in the support region, those located near the mid-span area have relatively low local stresses and high displacement deformations because of decreased rigidity of the structure. Hence, when placing openings in mid-span areas, it is crucial to increase the rigidity of the whole structure to avoid large deflections. In conclusion, this research has found out that even though web openings are necessary for structural functionality. Their positioning should be carefully optimized in order to ensure that there is a balance in terms of

structural safety and performance. The information gained from this research will go a long way in enhancing the design of steel structures.

5. Conclusions

A comprehensive analysis method utilizing Eurocode 3 and nonlinear finite element analysis through ABAQUS CAE software was used for the evaluation of the structural behaviour of simply supported steel box girders having circular openings in the webs under the simultaneous effects of axial displacement and bending loads. For optimizing the design process, an analysis regarding the effect of the position of the web opening on the stress and deformation behaviour is conducted systematically. The results indicate that the longitudinal location of the web opening can significantly impact the axial stress magnitude and structural utilization. Openings placed in close proximity to the supports or near concentrated load regions result in higher stress concentrations and higher utilization ratios of the bottom flanges, resulting in a higher probability of axial yielding and local buckling. Conversely, relocating the opening towards the mid-span region resulted in lower axial stress and improved stress redistribution, with the utilization ratios reduced by as much as 20.83% compared to the most critical opening configuration. This suggests improved structural efficiency and a reduced probability of strength-controlled failure. The finite element results not only substantiated the above trends but also revealed good convergence between the Eurocode and Abaqus-simulated performance, with agreement recorded in excess of 85% for all studied cases. Vertical deflection was largely insensitive to opening location and lateral displacement was negligible due to the high torsional stiffness of the box section; however, mid-span openings were associated with higher levels of global displacement, indicating the need to also consider serviceability criteria in addition to strength requirements. Therefore, even as mid-span openings result in increased efficiency in terms of structure. It is important that proper verification be done for compliance with serviceability requirements and deformation limits to avoid cases where too much deflection occurs. The results suggest that openings should be located away from regions of high stress concentration near supports and application

points of loads to reduce failure risk. The Eurocode–finite element approach implemented in this study is therefore a suitable and practical method to determine web opening placement in steel box girders. The high degree of concordance between the results of the predictions made by Eurocode and those obtained from nonlinear finite element analyses further validates the reliability of the proposed assessment framework for use in practical structural engineering design for enhanced structural safety, material efficiency, and uncertainty minimization during the verification stage of structural design. In consideration of the findings, future structural designs must ensure that any openings on webs must not be positioned near support zones or concentrated load zones but in lower shear stress zones near mid-span positions for enhanced structural safety and efficiency. The shift in structural response behavior from local flange yielding near support zones to deformation control near mid-spans necessitates region-specific reinforcement strategies and stiffness controls based on the position of the opening.

Author Contributions

Conceptualization, H.M.A.-J. and O.M.A.; methodology, H.M.A.-J.; software, L.M.S.; validation, H.M.A.-J., O.M.A. and L.M.S.; formal analysis, H.M.A.-J.; investigation, H.M.A.-J.; resources, O.M.A.; data curation, L.M.S.; writing—original draft preparation, H.M.A.-J.; writing—review and editing, O.M.A. and L.M.S.; visualization, L.M.S.; supervision, O.M.A.; project administration, O.M.A.; funding acquisition, O.M.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data that support the findings of this study, including finite element models, simulation outputs, and Eurocode-based analytical calculations, are available from the corresponding author upon reasonable request. No restrictions apply to the availability of the data for research and academic purposes.

Conflicts of Interest

The authors declare no conflict of interest. This research received no external funding.

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