The Effect of Expansion Ratio, Opening Size, and Prestress Strand on the Flexural Behavior of Steel Beams with Expanded Web using FEA

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ABSTRACT

The expanded web depth of steel beams leads to improved strength and stiffness. In some design scenarios, such as cellular, castellated, or expanded steel beams, increasing the depth of the web improves the strength and performance of the steel beam. The expanded web of steel beams can be accomplished by creating a horizontal cutting in the web and then adding a plate between the two web section halves, which are called spacer plates. This method leads to improved stiffness and strength. Numerical models have been developed to accurately predict the properties of these beams. This study investigates the use of incremental plates to increase the depth of hot-rolled wide-flange steel beams. The experimental results were validated first with the Finite Element (FE) numerical model created by ABAQUS software, and then Finite Element Analysis (FEA) methods were used to create and analyze new numerical models by considering parameters that provided more models at a lower cost. The load-mid-span deflection curve behavior of both models (experimental and theoretical) was similar. Also, the load-deflection behavior of steel beams with two types of openings was studied. For the first type of opening (B1 NUM), with a smaller opening width of 30 mm and a higher hole number (24), the ultimate load increased by 53%, 111%, and 184%, the deflection at 0.95 Pu increased by 160%, 293%, and 81% of beams with ratio 150%, 200%, and 250% compared with the reference beam. For the second type of opening (B2 NUM), with a larger opening width of 60 mm and smaller hole number (12), the ultimate load capacity increased by 51%, 147%, and 177%, for beams with a ratio of 150%, 200%, and 250%, compared with the reference beam. The deflection at 0.95 Pu increased by 46% and 15% for beams with a ratio of 150%, and 200%, and decreased by 8% for beams with a ratio of 250%. Accordingly, for the first type of opening, the expanded ratios of 150% and 200% performed best with a reduction of only 1%-12% in the ultimate load capacity. However, for the second type of opening, the beam with a ratio of 250% performed better than the first type. Using prestress strands may highly improve steel beams' performance with the expanded webs containing openings by creating a stronger section that can withstand higher loads and exhibit improved structural performance, especially from beams with a ratio of 150%.

Keywords-Vierendeel mechanisms; expansion ratio; web opening ratio; web post-buckling; prestress strand

I. INTRODUCTION

The expanded web depth for steel beams with openings leads to improved strength and stiffness [1]. In some design scenarios, such as cellular, castellated, or expanded steel beams, increasing the depth of the web ameliorates the strength and performance of the steel beam [2, 3]. The use of web-opening steel beams in modern buildings has several benefits over traditional I-section components. These advantages include enhanced visual appeal from a design perspective, an increased strength/weight ratio, and the ability to integrate utilities like ducts, electrical, or pipe conduits without compromising the structural integrity of the beam. This beam type is preferred in constructions with large spans like stadiums, bridges, and multistory buildings due to its ability to simplify installation and maximize area use [3]. Nevertheless, openings in the steel beam cause the beams to become less stiff, which increases their deflection, reduces their shear capacity, modifies their failure modes, and necessitates more intricate design considerations. Steel beams with expanded web are more expensive to fabricate than standard plain webbed beams. Furthermore, residual stresses are introduced into the steel beams by the opening process, which may have an impact on their structural behavior. The design procedure must take these residual stresses into account as they lower the critical buckling load. On the other hand, over the past 20 years, the use of expanded steel beams with openings has increased in popularity. This type of steel beams is governed by defined design guidelines and practice norms that are regularly updated to take into account new findings and technological developments [4-6]. There might be apertures or not in the enlarged steel beams. The steel beam's stiffness and strength are improved when compared to the original (hot rolled) component [7].

It is crucial to remember that technical standards and rules should be followed while designing and installing increment plates. It is advised to seek advice from a structural engineer or another expert in the field of steel construction to guarantee appropriate planning and execution for a secure and efficient development of the steel web [8, 9]. If stiffeners are supplied in the proper quantity, size, and placement, beams with apertures can be utilized to replace solid beams that meet the same specifications. Authors in [10, 11] pointed out that the presence of web holes in the steel beams might result in less weight and better structural performance. On the other hand, addressing the repair and reinforcement of deteriorated, damaged, and substandard infrastructure stands as a significant challenge for structural engineers across the globe [12]. However, there is a lack of literature survey on the behavior of steel beams with expanded web with horizontal cutting patterns and there are no clear data on research that deals with the strengthening technique of steel beams with expanded web with horizontal cutting patterns. The behavior of such beams under two-point bending will be simulated through nonlinear FEA utilizing the ABAQUS software. Steel beams with different expanding web ratios (200% and 250%), opening ratio of 24%, and with two types of openings, along with pre-stressed strands with expanding web containing openings were considered in the experimental and numerical work.

II. METHODOLOGY

A. *Steel Beam Modeling*

To simulate a four-point loading test on steel beams with expanded webs, an FE model was developed in ABAQUS. The beam was modeled using shell elements for the steel beams and incremental plates, whereas solid elements were used for the plates under load and above the supports [13]. When modeling plastic materials in ABAQUS, the Cauchy stress and the logarithmic plastic strain are utilized. However, to compute the material properties in a tensile coupon test, nominal stress, and engineering strain are initially obtained. As a result, it is necessary to convert these values to true stress and plastic true strain using specific procedure details [14, 15]. To represent the welds between the parts, a tie interaction was used in the model. This type of interaction allowed for the transfer of load between different parts without the need to explicitly model the welds. An appropriate mesh size was selected to ensure accurate results. The static Riks method was followed to analyze the model [8, 13, 16-18]. The Riks method is a powerful tool for predicting the buckling behavior of structures, as it accounts for large deformations and nonlinear material behavior. The model of steel beams with expanding web is illustrated in Figure 1.

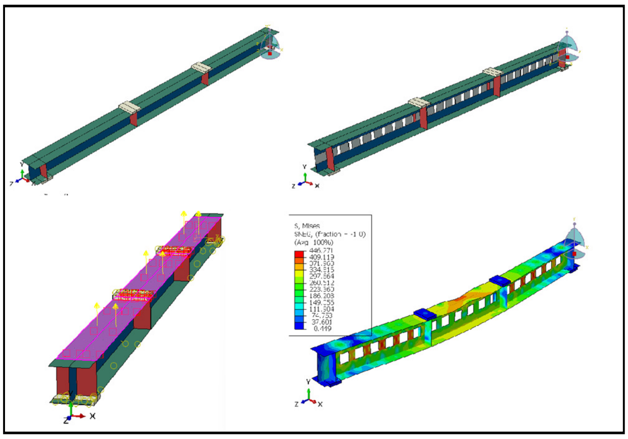
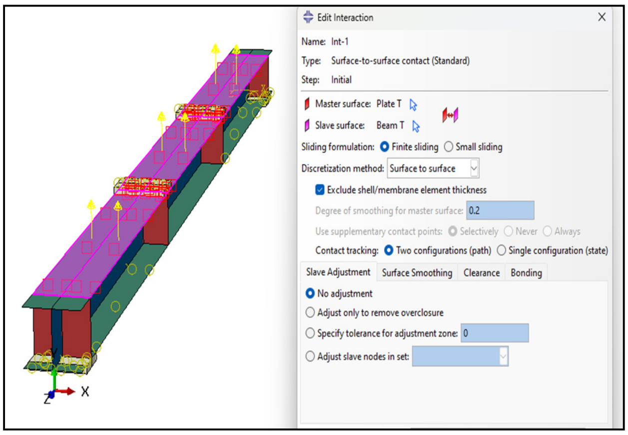


Fig. 1. Steel beam with expanding web in ABAQUS.

B. *Modeling the Contact Interaction between the Specimen Parts*

Tie constraints are utilized to connect two surfaces. For the steel beam interface, the W shape was taken for the master nodes with the slave nodes bearing stiffeners, and Tie constraints were used.



Edit Interaction

Name: Int-1

Type: Surface-to-surface contact (Standard)

Step: Initial

Master surface: Plate T

Slave surface: Beam T

Sliding formulation: ● Finite sliding ○ Small sliding

Discretization method: Surface to surface

☑ Exclude shell/membrane element thickness

Degree of smoothing for master surface: 0.2

Use supplementary contact points: ● Selectively ○ Never ○ Always

Contact tracking: ● Two configurations (path) ○ Single configuration (state)

● No adjustment

○ Adjust only to remove overclosure

○ Specify tolerance for adjustment zone: 0

○ Adjust slave nodes in set:

Fig. 2. Contact interaction between W shape and loading plate.

C. *Material Modeling (Steel Modeling)*

When it comes to steel, the stress-strain relationship is linear elastic until the material yields and is fully plastic between the yielding point and the kick-off to strain. In this paper, the standard hot-rolled steel HE160A was adopted in this infestation to fabricate the steel beam with the physical characteristics detailed in Table I. The steel grade used in this study is S235. According to the European standard EN 10025-2, S235 steel has a minimum yield strength of 235 MPa and a tensile strength of 360-510 MPa. Additionally, the modulus of elasticity is 210 GPa, the Poisson's ratio is 0.30, and the density is 7.85 g/cm^3. These mechanical properties make S235 a commonly deployed structural steel grade in various industries, including construction and engineering [14]. To implement the strengthening technique, plates with the mechanical characteristics in Table II were used as stiffeners and increment plates.

TABLE I. STEEL SECTION PROPERTIES

Section	He160a
G (kg/m)	30.4
h (mm	152
tf (mm)	9
tw (mm)	6
A $(mm)^2$	38.8
r (mm)	15
I $(mm)^4$	1673
Sx $(mm)^3$	220.1
Zx $(mm)^3$	245

TABLE II. PLATE MECHANICAL PROPERTIES

Thickness, (mm)	Yield Stresses, (MPa)	Ultimate Stress, (MPa)
6	235	360

III. MODEL VALIDATION

The accuracy and reliability of the FEA predictions comprehensively rely on the fidelity of the underlying computational models. Validation, therefore, emerges as a critical step in the FEA workflow, aimed to assess the model's ability to replicate real-world behavior. In this paper, the validation work utilized experimental load versus deflection data to assess the accuracy and reliability of the FEA regarding the simulation of a steel beam with an expanded web. Accordingly, a comparison is performed between the numerical results from the FEA simulations and the experimental results acquired from [19]. The results are shown in Figures 3-7.

- The numerical results of ultimate load were different than the experimental results by 3%, 6%, 1%, 9%, and 8%. Furthermore, the numerical result of carrying loads at deflection service point (12 mm) was less than the experimental result by 39%, 13%, 32%, and 32% for RB01, G1B1, G1B2, G2B1, and G2B2 beams, respectively.
- The numerical results of the mid-span deflection at 0.95 Pu differed from the experimental results by only 27%, 22%, 11%, 27%, and 29% for RB01, G1B1, G1B2, G2B2, and G2B1 beams, respectively. Moreover, the numerical result of the deflection at the yield point was less than the experimental results by 19%, 29%, 32%, 13%, and 54%, respectively.

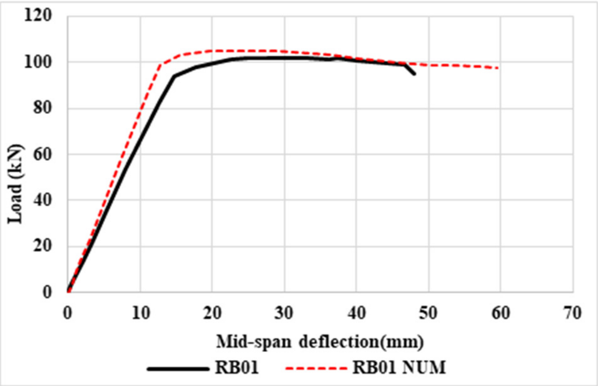


Fig. 3. Load-mid span deflection curve of thre experimental and numerical results for beam RB01.

- The load-mid span deflection curve behavior of both models (experimental and theoretical) is similar.
- From the above, it is concluded that the experimental test results are less sensitive than the numerical analysis results. Regarding the ultimate load, it is clear that the numerical and experimental results are in good agreement.

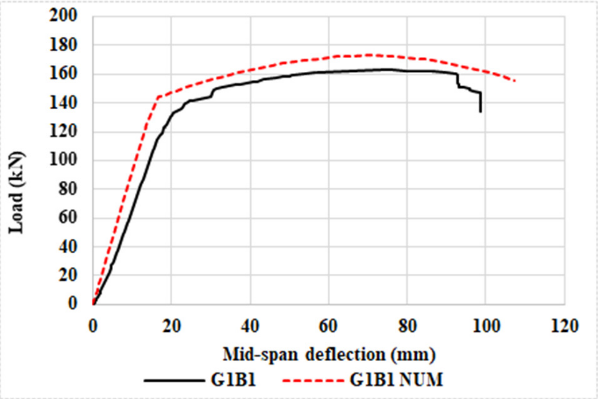


Fig. 4. Load-mid span deflection curve of thre experimental and numerical results for beam G1B1.

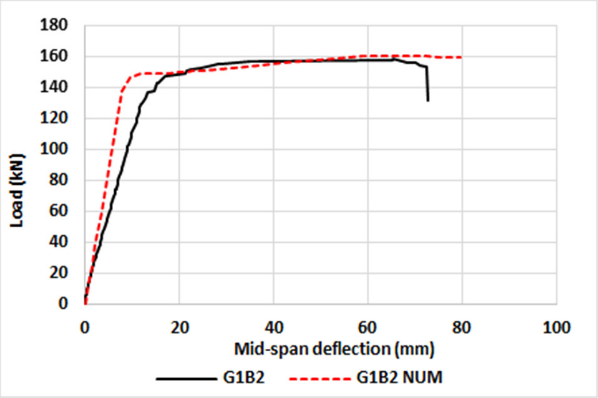


Fig. 5. Load-mid span deflection curve of thre experimental and numerical results for beam G1B2.

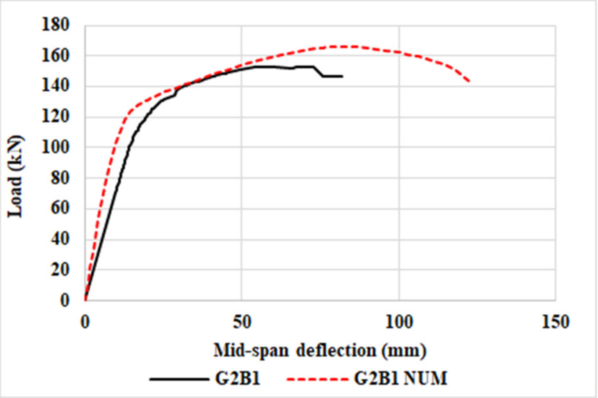


Fig. 6. Load-mid span deflection curve of thre experimental and numerical results for beam G2B1.

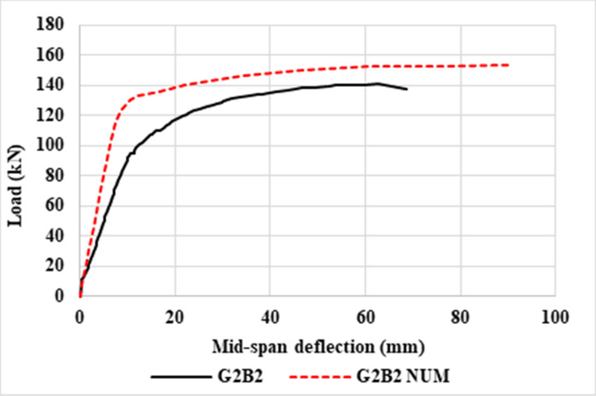


Fig. 7. Load-mid span deflection curve of thre experimental and numerical results for beam G2B2.

IV. CASE STUDIES FOR THE NEW NUMERICAL MODELS

A. *First Case*

Steel beams with different expanding web ratios (150%, 200%, and 250%) with an opening ratio equal to 24%, and with two types of openings, as observed in Figures 8 and 9. The effects of expanding the web depth of the steel beams on the load-mid span deflection behavior are demonstrated in Figures 10 and 11.

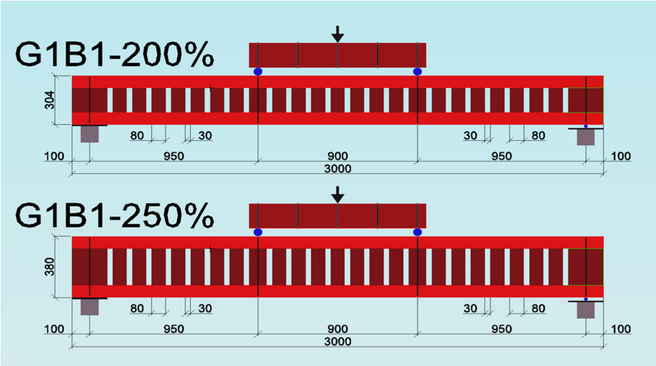


Fig. 8. Dimensions of beams G1B1-200% and G1B1-250%.

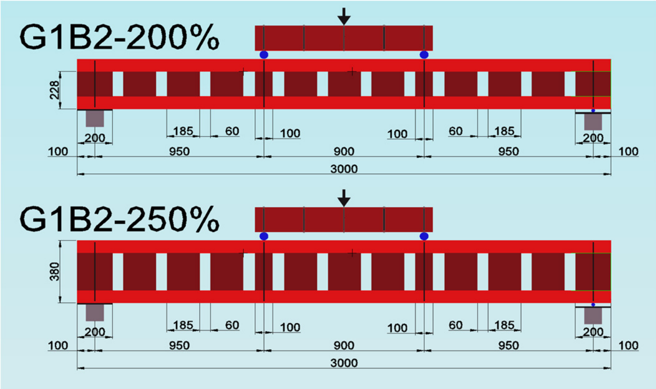


Fig. 9. Dimensions of beams G1B2-200% and G1B2-250%.

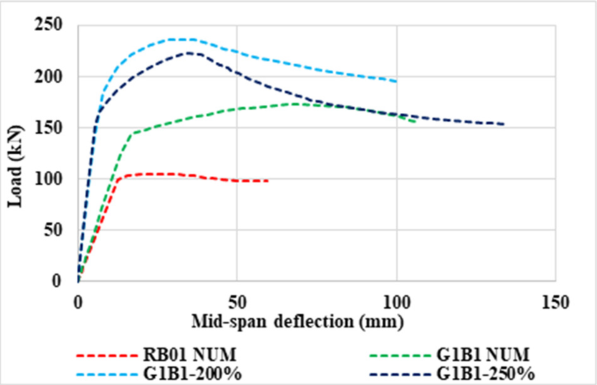


Fig. 10. Load-deflection curves of beams RB01 NUM, G1B1 NUM, G1B1-200%, G1B1-250%.

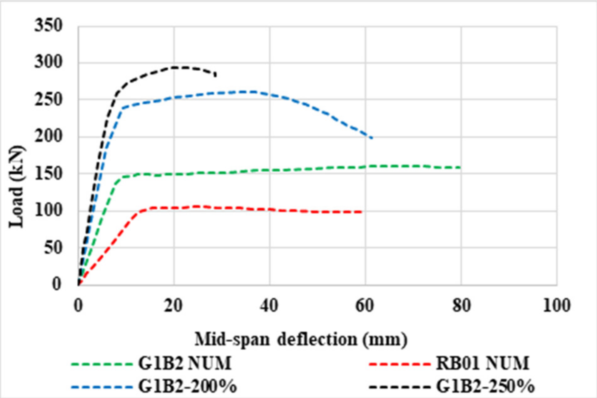


Fig. 11. Load-deflection curves of beams RB01 NUM, G1B2 NUM, G1B2-200%, G1B2-250%.

The associated beams are separated into two groups according to their web opening number and width as depicted in Figures 8 and 9. Accordingly, the first numerical type (B1 NUM) has a smaller opening width (30 mm) and higher hole number (24), and the second numerical type (B2 NUM) has a larger opening width (60 mm) and smaller hole number (12)

1) *Ultimate Load Results of B1 NUM*

The ultimate loads increased by 53%, 111%, and 184%. In addition, at the deflection service point (12 mm), the carrying loads of beams with an expanded ratio of 150%, 200%, and 250% increased by 10%, 108%, and 122%, compared with the reference solid beam with no expanded ratio (RB01).

2) *Mid-Span Deflection Results of B1 NUM*

The deflection at 0.95 Pu of 150%, 200%, and 250% beams increased by 160%, 293%, and 81%. Furthermore, the deflection at the yield point of the 50% beam increased by 41% and of the 200% and 250% beams decreased by 27% and 8%, compared with the reference beam (RB01).

For the steel beams with an expanded web and a 24% opening ratio with 30 mm opening width, and 24 openings, according to the analysis of the load-deflection behavior and by comparing the former to the reference beams with the same expansion ratio, the beams with expansion ratio of 150%, 200% performed most effectively with a reduction in the ultimate load capacity by just 1%-12%. The beams with an expansion ratio of 250%, have no economic viability with a reduction in the load capacity of 106%.

3) *Ultimate Load Results of B2 NUM*

The ultimate load capacity increased by 51%, 147%, and 177%. Furthermore, at the deflection service point (12 mm), the loads increased by 146%, 151%, and 192% for beams with 150%, 200%, and 250% ratio, compared with the reference solid beam (RB01).

4) *Mid-Span Deflection Results of B2 NUM*

The deflection of 150%, and 200% beams at 0.95 Pu increased by 46%, and 15% and for the 250% beam, it decreased by 8%, compared with the reference beam (RB01). Additionally, the deflection at the yield point of beams G1B2-150%, G1B2-200%, and G1B2-250% decreased by 13%, 18%, and 23% compared with the reference beam (RB01).

The steel beams with the expanded web that have 160 mm opening width, and 9 openings according to the analysis of the load-deflection behavior and by being compared with the reference beams with the same expansion ratio, outperform the first type (B1) with a reduction in load capacity of 66%. However, the steel beams with expansion ratios of 150%, and 200% have a reduction in ultimate load by only 1-13%.

Based on the above, it was determined that an increase in the ultimate load may result from the expansion of a steel beam web with a 24% opening ratio. This behavior was comparable to that of the steel beam expanded web with a 48% opening ratio. Flexural capacity improvement is associated with an increased section stiffness following the expansion process.

B. *Second Case*

Prestress strands were adopted on steel beams with different expanding web ratios and 48% opening ratio as shown in Figures 12-14. Accordingly, the first numerical type (B1 NUM) has a smaller opening width (80 mm) and a higher hole number (18) and the second numerical type (B2 NUM) has a larger opening width (16 0mm) and a smaller hole number (9).

The influence of the prestress strands as a strengthening tool on the load-mid span deflection behavior of the steel beams with an expanded web and containing 48% opening ratio is displayed in Figures 15-20.

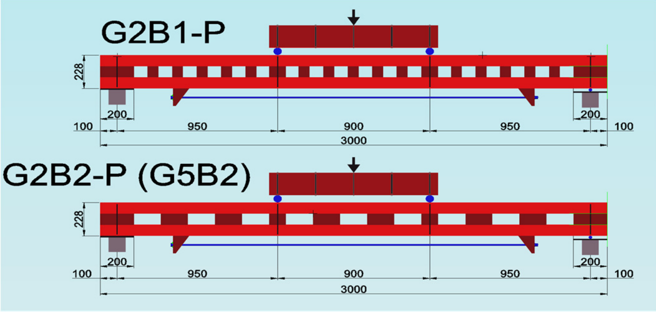


Fig. 12. Dimension of beams G1B1-P and G2B2-P.

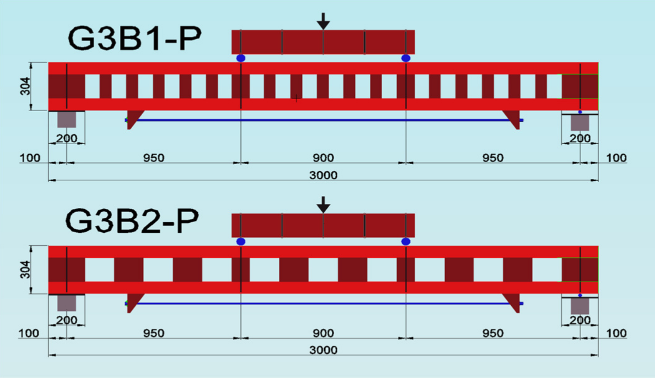


Fig. 13. Dimensions of beams G3B1-P and G3B2-P.

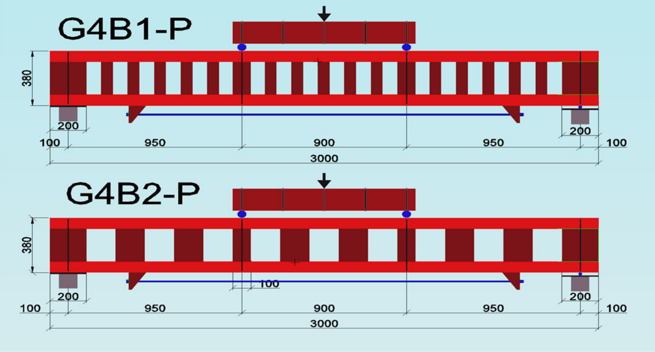


Fig. 14. Dimensions of beams G4B1-P and G4B2-P.

1) *Ultimate Load Results of B1 NUM*

The ultimate loads of beams G2B1-P, G3B1-P, and G4B1-P increased by 74%, 56%, and 33%, when compared with beams G2B1, G3B1, and G4B1. At the deflection service point (12 mm), the carrying loads increased by (30%, 59%, and 49%), respectively.

2) *Mid-Span Deflection Results of B1 NUM*

The deflection at 0.95 Pu of beam G2B1-P increased by 36% and decreased by 7%, and 47% for beams G3B1-P and G4B1-P. The compared reference beams were G2B1, G3B1, and G4B1, respectively.

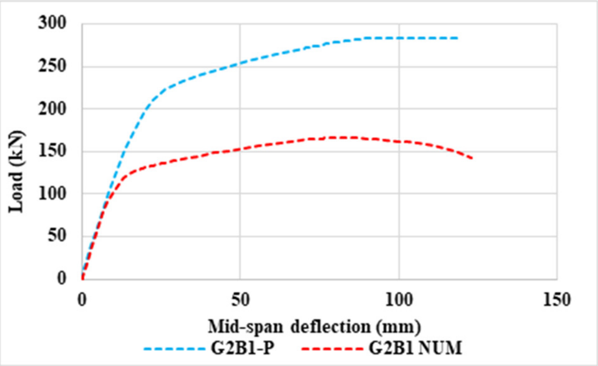


Fig. 15. Load-midload-mid span deflection numerical result of beams G2B1 and G2B1-P.

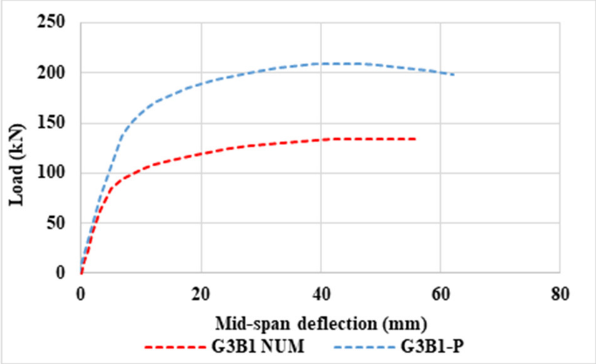


Fig. 16. Load-midload-mid span deflection numerical result of beams G3B1 and G3B1-P.

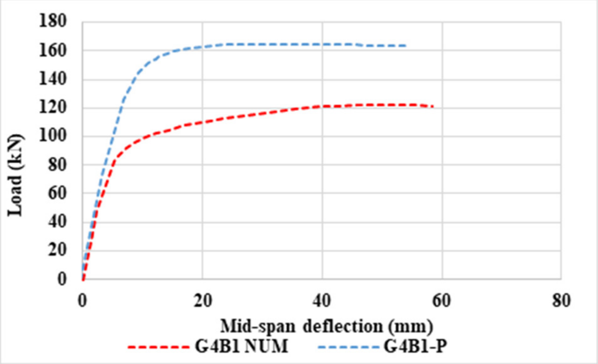


Fig. 17. Load-midload-mid span deflection numerical result of beams G4B1, and G4B1-P.

3) *Ultimate Load Results of B2 NUM*

The ultimate loads of beams G2B2-P, G3B2-P, and G4B2-P increased by 71%, 57%, and 57% in comparison with beams G2B2-P, G3B2-P, and G4B2-P. Moreover, at the deflection service point (12 mm), the loads increased by 58%, 55%, and 58%, respectively.

4) *Mid-Span Deflection Results of B2 NUM*

The deflection at 0.95 Pu of beams G2B2-P and G3B2-P decreased by 22% and 26% and for beam G4B2-P increased by 24%, in comparison with beams G2B2, G3B2, and G4B2, correspondingly.

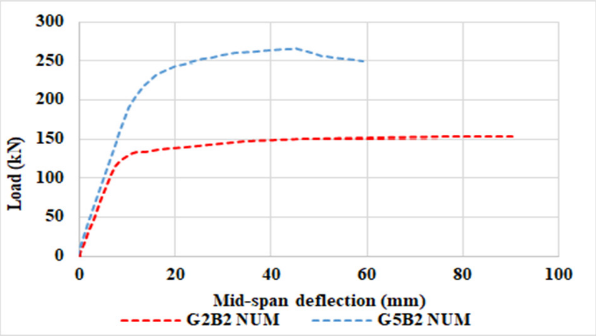


Fig. 18. Load-mid span deflection numerical result of beams G2B2 and G2B2-P or G5B2 NUM.

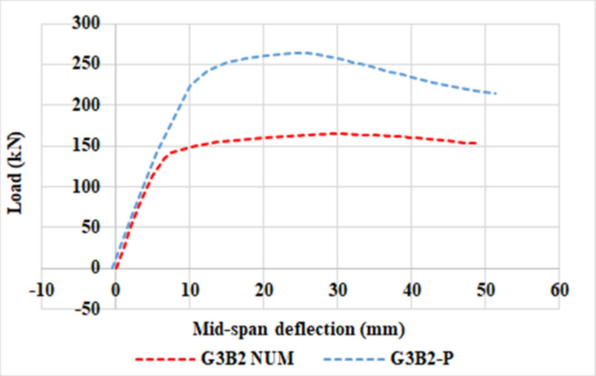


Fig. 19. Load-midload-mid span deflection numerical result of beams G3B2 and G3B2-P.

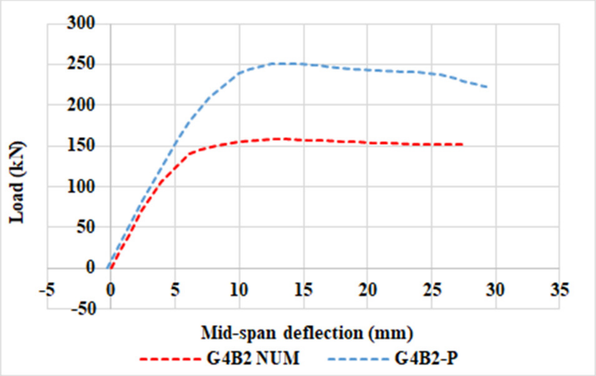


Fig. 20. Load-midload-mid span deflection numerical result of beams G4B2 and G4B2-P.

It can be noted that there is a greater influence of the expanding web of a steel beam on the ultimate carrying load and deflection compared with the carrying the load at the deflection service point (12 mm) and yield deflection.

According to the above observations, it was concluded that the best result from using prestress strands was found at G2B1 and G2B2. Also, it was concluded that using prestress strands can highly improve the performance of steel beams with expanded webs that contain openings by creating stronger sections that can withstand higher loads and exhibit improved structural performance, especially from a beam with 150% expansion ratio.

C. *Third Case*

In this case, prestress strands were utilized on steel beams with different expanding web ratios and 24% opening ratio as manifested in Figures 21 and 22. The first numerical type (B1 NUM) has a smaller opening width (30 mm) and a higher hole number (24), whereas the second numerical type (B2 NUM) has a larger opening width (60 mm) and a smaller hole number (12).

The influence of using prestress strand as a strengthening device for steel beams with a varying expanded web ratio and 24% opening ratio on the load-mid span deflection behavior is portrayed in Figures 23-25.

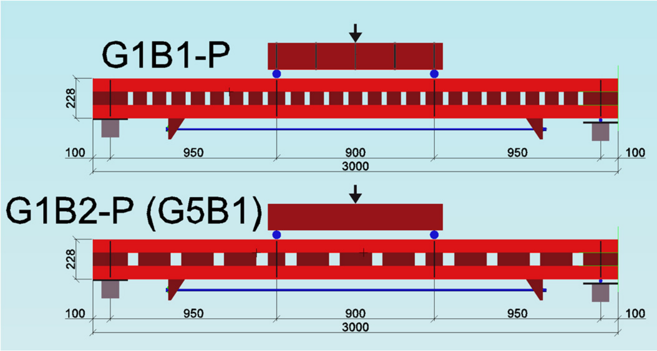


Fig. 21. Dimensions of beams G1B1-P and G1B2-P.

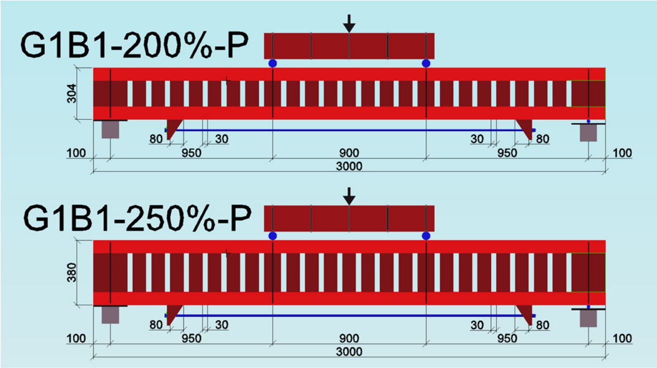


Fig. 22. Dimensions of beams G1B1-200-P% and G1B1-250%-P.

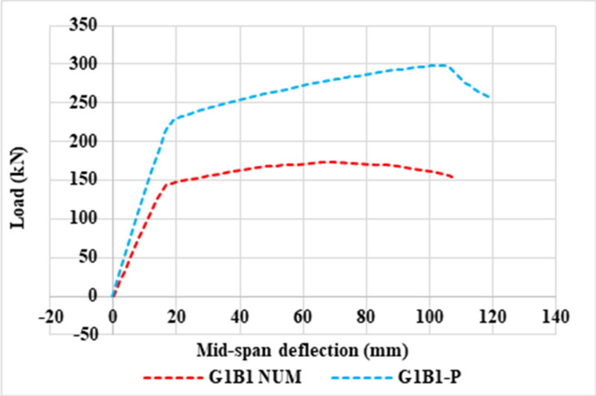


Fig. 23. Load-mid span deflection numerical result of beams G1B1-150% and G1B1 -150%-P.

1) Ultimate Load Results of B1 NUM

The ultimate loads of beams G1B1-P-150%, G1B1-P-200%, and G1B1-P-250% increased by 73%, 62%, and 35%, compared with beams G1B1-150%, G1B1-200%, G1B1-250%, respectively. Moreover, at the deflection service point (12 mm), the carrying loads increased by 32%, 66%, and 24%.

2) Mid-Span Deflection Eesults of B1 NUM

The deflection at 0.95 Pu of beams G1B1-P-150%, G1B1-P-200%, G1B1-P-250% increased by 133% and 13% and decreased by 13%, when compared with beams G1B1-150%, G1B1-200%, G1B1-250%, correspondingly.

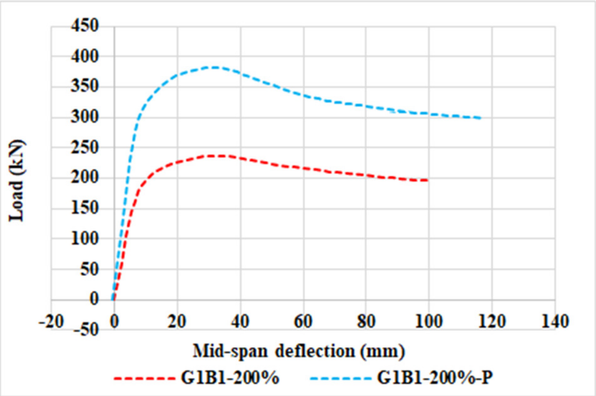


Fig. 24. Load-mid span deflection numerical result of beams G1B1-200% and G1B1 -200%-P.

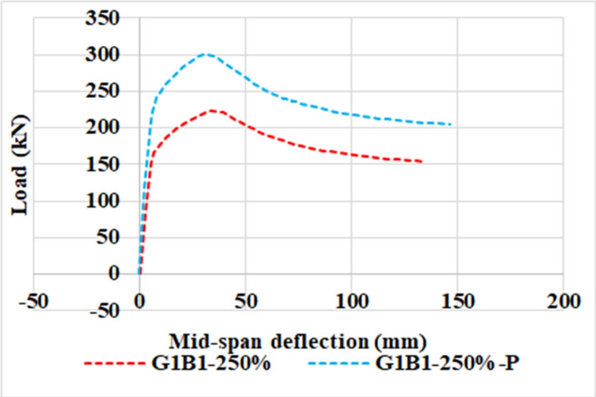


Fig. 25. Load-mid span deflection numerical result of beams G1B1-250% and G1B1 -250%-P.

3) Ultimate Load Results of B2 NUM

The ultimate load of beams G1B2-P-150%, G1B2-P-200%, and G1B2-P-250%, was increased by 85%, 68%, and 53%, respectively, in comparison with beams G1B2-150%, G1B2-200%, and G1B2-250%. Moreover, at the deflection service point (12 mm), the carrying loads increased by 60%, 67%, and 54%), accordingly.

4) Mid-Span Deflection Results of B2 NUM

The deflection at 0.95Pu of beams G1B2-P-150%, G1B2-P-200%, and G1B2-P-250% decreased by 44% and 7% and increased by 17%, in comparison with beams G1B2-150%, G1B2-200%, G1B2-250%, respectively.

From the above findings, it was concluded that the best results from using a prestress strand were found at beams G1B1 and G1B2. Accordingly, it was concluded that using prestress strands as a strengthening means for steel beams with expanded web, 24% opening ratio on the load-mid span deflection behavior section, leads to the same behavior demonstrated by the beams with 48% opening ratio, which can withstand higher loads and exhibit improved structural performance, and especially the beams with 150% expanding web ratio, smaller opening width, and higher holes number.

V. CONCLUSION

After exploring the results obtained from the current study, this section will highlight the key findings and their implications. Based on the outcomes of the experimental research, the following conclusions were drawn:

- For the ultimate load results, the difference between the experimental and numerical results for the reference beam was 3% and for the steel beam with an expanded solid web ranged from 4% to 7%. For the mid-span deflection at 0.95 Pu, the difference between the experimental and numerical results of the reference beam was 27% and for the steel beam with an expanded solid web ranged from 0% to 23%.
- For the ultimate load results, the difference between the experimental and numerical results of a steel beam with an expanded web containing openings was from 1% to 16%. However, for the mid-span deflection at 0.95 Pu, the difference was from 4% to 27%.
- The experimental test results are less sensitive than the numerical analysis ones obtained using ABAQUS software.
- Regarding the load-deflection behavior of the steel beam with expanded web ratios of 150%, 200%, and 250%, opening ratio of 24%, and two types of openings, for the first type of openings (B1 NUM) with a smaller opening width (3 0mm) and higher hole number (24), the ultimate load increased by 53%, 111%, and 184%, the deflection at 0.95 Pu increased by 160%, 293%, and 81%, respectively, compared with the reference beam. For the second type of opening (B2 NUM) with a larger opening width (60 mm) and smaller hole number (12), the ultimate loads capacity increased by 51%, 147%, and 177%. The deflection at 0.95 Pu of steel beams with expanded web ratios of 150%, and 200% increased by 46%, and 15%, and for the expanded web ratio of 250% decreased by 8% compared with the reference beams.
- For steel beams with the expanded web and 24% opening ratio with 30 mm opening widths, and 18 openings, according to the load-mid span deflection behavior, the beams with expansion ratios of 150% and 200% performed most effectively, reducing the final load capacity by just 11% and 23%, respectively. Based on the examination of the load-mid span deflection behavior and the loss in load capacity of 106% when compared to solid expanded steel beams with the same expansion ratio, the beams with an expansion ratio of 250% are not economically viable.
- For steel beams with an expanded web that have 160 mm opening width and 9 openings, the beam with an expansion ratio of 250% performed better than the first type according to the load-mid span deflection behavior with a reduction in the load capacity by 40%. Comparing the solid expanded steel beam with the same expansion ratio to the beam with expansion ratios of 150% and 200%, the load capacity of the former is reduced by 13% and 11%, respectively.
- Using pre-stress strands can highly improve the performance of the steel beam with expanded webs containing openings by creating a stronger section that can withstand higher loads and exhibit improved structural performance, especially when compared to beams with 150% ratio.
- Including higher material and manufacturing costs, increased weight, connection challenges, space constraints, buckling concerns, serviceability issues, fabrication complexities, and potential unavailability of specialized sections, a careful consideration of the project requirements and trade-offs is crucial for an optimal design.
- The current study can be extended to include different loads, beam geometry, support conditions, strengthening techniques, and strength.

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