Behaviour of longitudinally stiffened stainless-steel plate girder under combined bending and shear

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ABSTRACT

Due to the high corrosion resistance, the use of stainless steel is increased in a wide range of environment in the last two decades. The behaviour of stainless steel is different from that of carbon steel, especially in a stress-strain relationship. Stainless steel has a rounded stress-strain curve, whereas carbon steel exhibits a sharp yield point in the stress-strain curve. Stainless steel has better strain hardening capacity and possesses high ductility. Stiffeners are generally utilised in plate girder for increasing the load-carrying capacity by providing better resistance against buckling of web panels. The existing study related to austenitic stainless steel plate girder studied the effect of longitudinal stiffener placed at the centre of the web panel alone. Present work uses to optimise position of longitudinal stiffener in stainless steel plate girder subjected to combined bending and shear. The behaviour is analysed by using finite element software ABAQUS. The optimum location for longitudinal stiffener in long-span stainless steel plate girder under combined bending and shear was identified and compared the results with the standard design codes.

Keywords: longitudinal stiffeners, stainless steel, plate girder, combined bending and shear,

1 INTRODUCTION

Due to the absence of sharp yield point stress-strain curve, stainless steel shows different material behaviour compared to carbon steel. The characteristics of stainless steel makes it more suitable for structural industry. In plate girders, vertical stiffeners are usually provided to improve the stability of web plates and the longitudinal stiffeners are resisting the lateral deflection of web plate. Usually, longitudinal stiffeners are provided for deep plate girders with slender webs. Many studies were conducted by various researchers in carbon steel plate girder to understand the behaviour of plate girder with longitudinal stiffeners. Longitudinal stiffener increases the load-carrying capacity of carbon steel plate girder. Inadequate stiffness causes unstable failure modes in plate girders. So, the design of a longitudinal stiffener requires more attention [1]. The main cost associated with the use of longitudinal stiffeners arises from fabrication cost than the stiffener material cost [2]. 0.2 times the depth of the web plate from the loaded flange was suggested as the optimum location for a single longitudinal stiffener by various international standard codes [3]. Alinia et al. [3] found that the optimum position depends upon the flexural rigidity and panel aspect ratio. The presence of longitudinal stiffener in plater girder under combined bending and shear increases the buckling capacity [4]. From the studies of Vu et al. [5] the optimum location for longitudinal stiffener in plate girder under pure bending which was similar to the optimum location obtained in plate girder with predominant shear behaviour. Estrada et al. [6] experimented with stainless steel plate girder by placing the longitudinal stiffener at the mid-height of the web plate. They observed a considerable increase in ultimate load-carrying capacity in the stainless-steel plate girder.

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Most of the existing studies related to the effect of longitudinal stiffeners in stainless steel plate girder were carried out on short span plate girder, which has a shear response. The current study was conducted to investigate the effect of longitudinal stiffener in long-span stainless steel plate girder under combined bending and shear. The studies of Chen et al.[7] reveals that, the load-carrying capacity of the plate girder web is highly influenced by the interaction of higher bending moment and shear force. In the present work, the numerical investigation was done by using commercial finite element software ABAQUS [8] v. 6.14. Several previous studies [9-12] confirmed the ability of ABAQUS software to produce accurate results. So the same modelling methods adopted in the present study. The longitudinally unstiffened numerical model was validated against the experimental study conducted by Chen et al. [7]. From their study on long-span stainless steel plate girder, the buckling failure was observed in the middle web panels. In the present work, the effect of position of longitudinal stiffeners in stainless steel plate girder within the middle web panel subjected to combined bending and shear was reported.

2 NUMERICAL MODELLING

2.1 Geometry

The present study initially simulates the experiment conducted by Chen et al. [7] numerically with suitable boundary conditions. The experimental setup and geometry of plate girder specimen are shown in figure 1. The specimen was having a nominal web depth of 600 mm and aspect ratio (a/h_w) of one. The other geometrical values marked in figure 1 are given as L=2556 mm, a=598.9 mm, e=80.2 mm, h_w=598.1 mm, b=180 mm, t_w=3.9 mm, t_f=7.72 mm, t_{ms}=12.59 mm and t_s=7.72 mm.

2.2 Material modelling

The stress-strain data of duplex (EN 1.4462) grade stainless steel obtained from the tensile coupon test conducted by Chen et al. [7] was used in this work which is listed in table 1. The material was modelled by using two-stage expressions proposed by Fernando et al. [13] as given in equation 1 and 2.

Table 1. Duplex stainless steel material properties

Grade	t (mm)	E_0 (MPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)	n
	3.9	204800	539.6	761.4	26.1	8.9
1.4462	7.72	188700	551.4	738.4	19.3	6.7
	12.59	184000	464.6	705.3	23.3	4.8

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \quad \text{for } \sigma \leq \sigma_{0.2} \qquad (1)$$

where σ and ε are the engineering stress and strain respectively. The other parameters are given as E_0 -Young's modulus, n- strain hardening exponent, $\sigma_{0.2}$-0.2 % proof stress.

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \ (\varepsilon_u - ((\sigma_u - \sigma_{0.2})/E_{0.2}) - \varepsilon_{0.2}) \left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \quad \text{for } \sigma > \sigma_{0.2} \qquad (2)$$

where $\varepsilon_{0.2}$ -strain corresponding to 0.2% proof stress, σ_u- ultimate stress and ε_u -strain corresponding to ultimate stress. $E_{0.2}$ is the tangent modulus at 0.2% offset strain given by equation 3. m is the second stage strain hardening parameter given by equation 4.

$$E_{0.2} = \frac{\sigma_{0.2} E_0}{\sigma_{0.2} + 0.002 n E_0} \qquad (3)$$

$$m = 3.5\left(\frac{\sigma}{\sigma_u}\right) + 0.1 \qquad (4)$$

The engineering stress-strain data were converted into true stress versus true strain form before defining the material in ABAQUS.

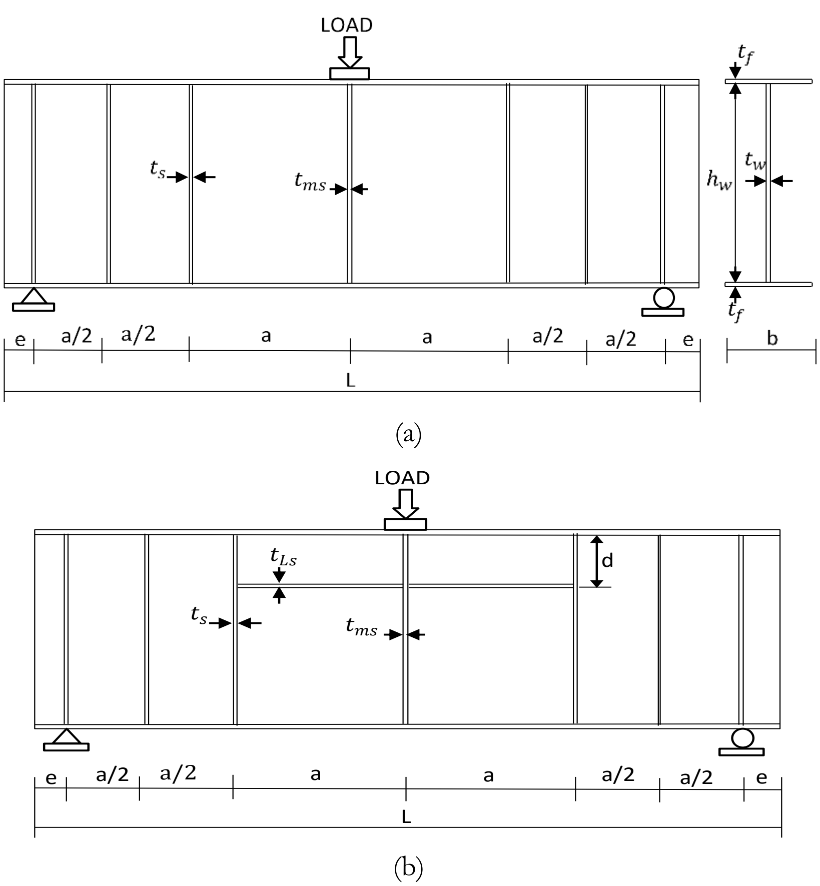


Figure 1. Geometry of plate girder (a) plate girder without longitudinal stiffener (b) plate girder with longitudinal stiffener

2.3 FE modelling

The S4R shell element with reduced integration available in ABAQUS was used to model the plate girder. The element edge dimension was finalised after a convergence study as depicted in figure 2. It was found that beyond 8500 elements the results tends to converge. The corresponding element edge dimension of 20mm×20mm was adopted for modelling. The meshed finite element model is shown in figure 3. The boundary conditions adopted were illustrated in figure 4, where the symbol u_x, u_y and u_z represent displacements along x, y, and z axis, respectively. In the figure θ_x, θ_y, and θ_z are rotations about to x, y, and z axis respectively. Lateral displacements were prevented to avoid lateral-torsional buckling.

The first elastic buckling mode obtained after the linear elastic buckling analysis was utilised as the shape imperfection with the chosen amplitude. The imperfection amplitude measured by Chen et al. [7] was incorporated in this work. Modified Riks method available in ABAQUS was used to perform the nonlinear analysis.

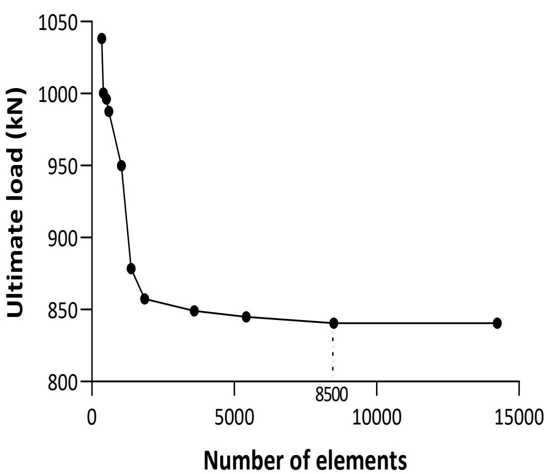


Figure 2. Convergence study of the finite element mesh

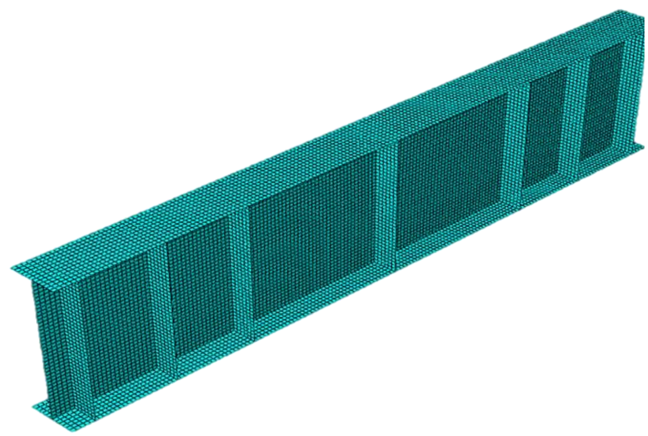
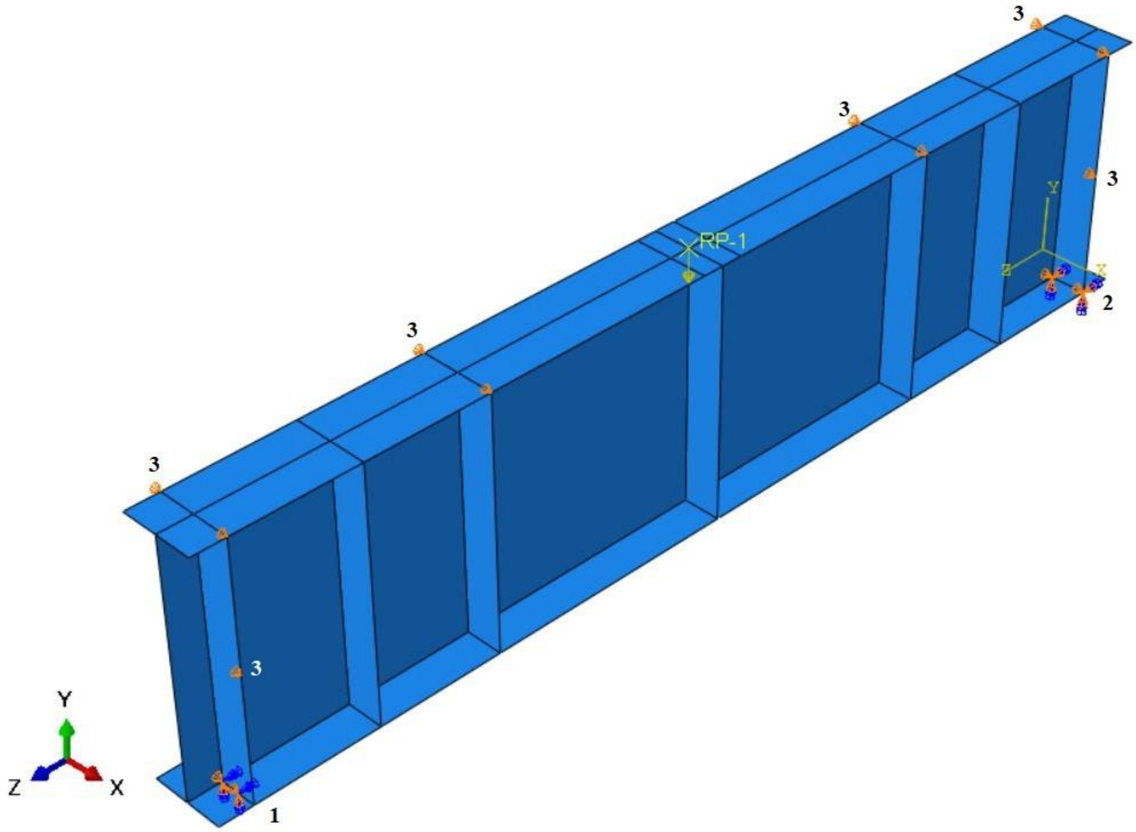


Figure 3. Meshed finite element model



Location	u_x	u_y	u_z	θ_x	θ_y	θ_z
1	1	1	0	0	1	1
2	1	1	1	0	1	1
3	1	0	0	0	0	0

0=free

1=restrained

Figure 4. Boundary conditions defined in FE models

2.4 Validation

The numerical results are compared with the experimental [7] results to confirm the accuracy of the FE model. In figure 5 the load-displacement curve obtained from the numerical analysis is compared with experimental [7] results. The percentage error of numerically obtained ultimate load with experimental ultimate load is -0.75% only. The FE and experimental failure modes given in figure 6 shows close similarity. Therefore, the finite element model can be considered as validated and can be used for further simulations.

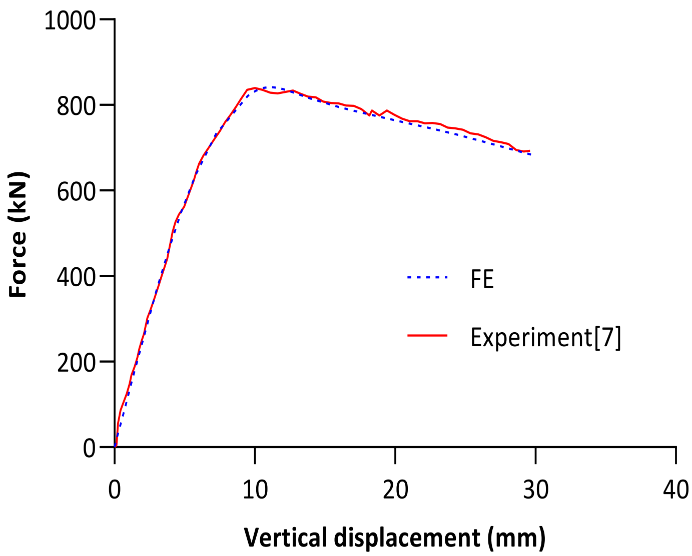


Figure 5. Comparison between test and FE load versus vertical displacement

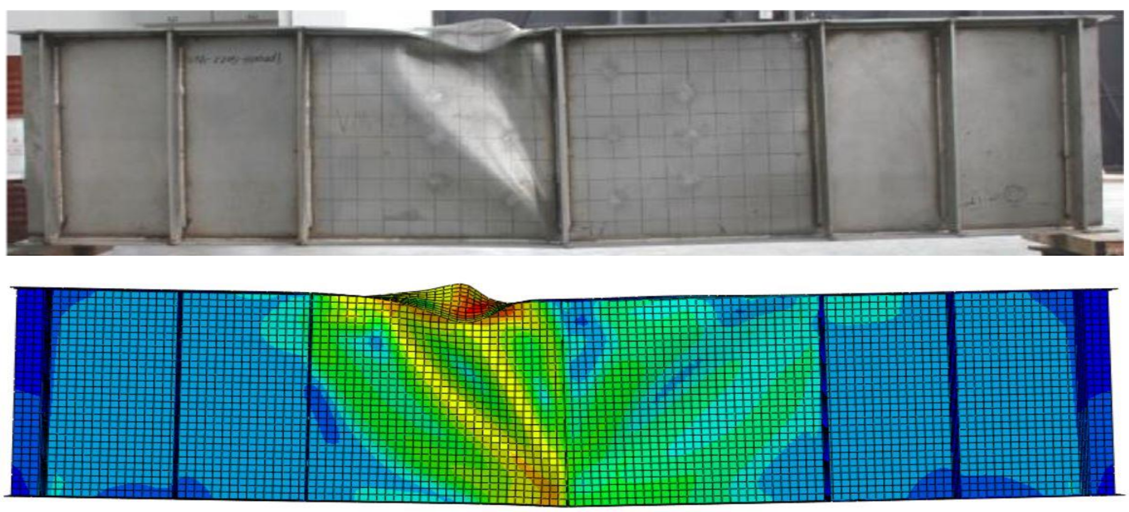


Figure 6. Comparison between test and FE failure modes

2.5 Parametric study

The parametric study was conducted in the validated model. The longitudinal stiffeners were provided only for middle web panels as shown in figure 1.b where the failure was occurring due to combined bending and shear. The longitudinal stiffness was provided on both sides of the web plate. The behaviour of plate girder with longitudinal stiffener at various position within the middle web plate was studied by varying a non-dimensional parameter d/h_w. The value of d/h_w varied from 0.1 to 0.9. The effect of web slenderness (t_w/h_w) was also studied by considering the slenderness values from 75 to 200.

3 RESULTS AND DISCUSSIONS

3.1 Effect of longitudinal stiffener

The effect of single longitudinal stiffener in the stainless-steel plate girder at different locations are graphically presented in figure 7. From the figure, it is clear that the stiffener provided in the compression region (between the neutral axis and loaded flange) effectively enhance the load-carrying capacity of a plate girder. Generally buckling is initiated near the loaded flange of a plate girder. Most of the design codes recommended the longitudinal stiffener position as 0.2 times web depth for carbon steel plate girders. In the case of stainless-steel long span plate girder also, the recommendations are considerable. More precisely, $0.25h_w$ was observed as an optimum position for a longitudinal stiffener. The effect of different longitudinal stiffener thickness (3mm to 12mm) was analysed at the optimum location and observed that the variation of thickness did not significantly affect the ultimate load-carrying capacity of the plate girder. The results substantiated the observations of Truong et al. [14] in steel plate girder under combined bending and shear. For all numerical analysis, 12 mm thick longitudinal stiffener was considered. Longitudinal stiffener at the optimum location increases the ultimate load by 31.87 percentage compared to longitudinally unstiffened plate girder. The load-displacement behaviour of the longitudinal stiffened plate girder and unstiffened plate girders are shown in figure 8. The presence of longitudinal stiffener increases both the ultimate load and the displacement corresponding to the ultimate failure load. On increasing the d/h_w ratio the displacement corresponding to the ultimate load was decreased which indicates that the longitudinal stiffener can significantly affect the ductile nature of the plate girder. The comparison of buckling mode shapes of plate girders with and without longitudinal stiffeners are shown in figure 9. The comparison indicates that longitudinal stiffener at the optimum location reduces the buckling area of the web plate. The failure mode is given in figure 10 also supports the previous observation. The reduction of the buckled area due to the presence of longitudinal stiffener improves the load-carrying capacity of a plate girder.

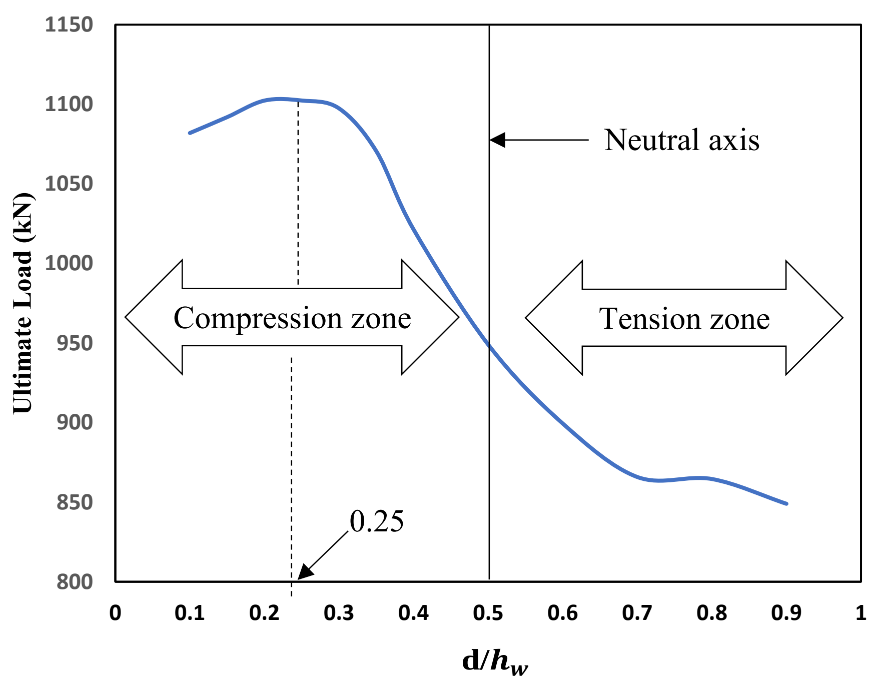


Figure.7. Effect of d/h_w ratio

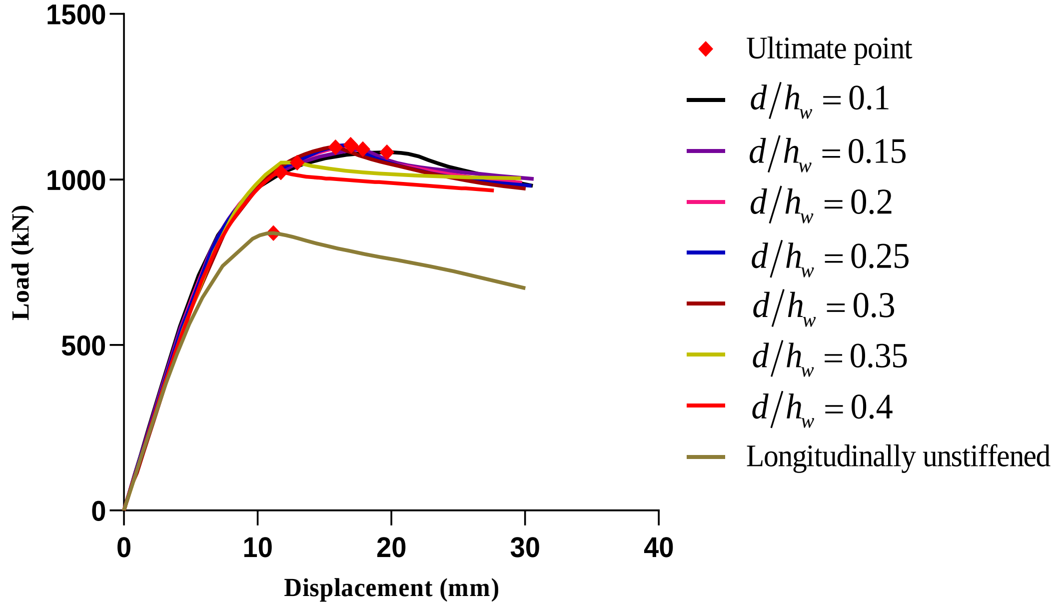
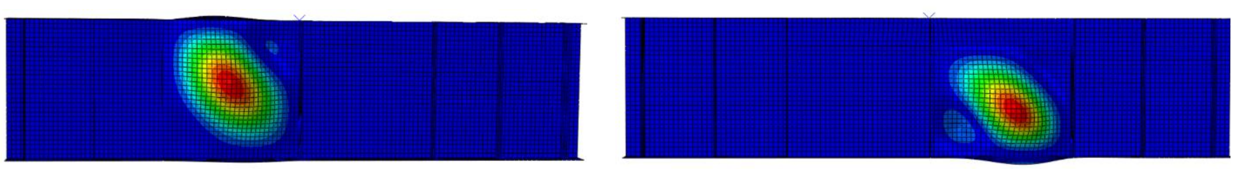
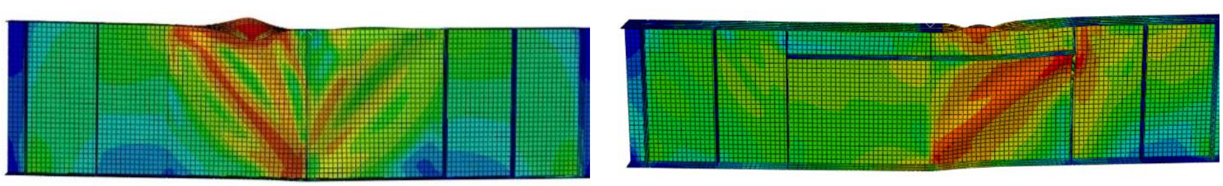


Figure. 8 Load-displacement behaviour of longitudinally stiffened and unstiffened plate girder



(a) (b)

Figure. 9. Comparison of buckling mode shapes (a) plate girder without longitudinal stiffener (b) plate girder with longitudinal stiffener



(a) (b)

Figure 10. Comparison of failure modes (a) plate girder without longitudinal stiffener (b) plate girder with longitudinal stiffener

A secondary longitudinal stiffener was placed at varying locations(d) in between the neutral axis and lower flange. To find the best location of second longitudinal stiffener along with a fixed longitudinal stiffener in compression zone at the optimum position $(0.25h_w)$ numerical simulations were done. A typical combination of longitudinal stiffeners is shown in figure 11. The combined effect of two longitudinal stiffeners with a varying position of the secondary stiffener is shown in figure 12. It was found that the best location for the second longitudinal stiffener was at the neutral axis within the tension zone. The buckling mode shape and failure mode of plate girder observed in the lowermost middle web plate area as shown in figure 13. Adding the second longitudinal stiffeners at the optimum location increased the ultimate load by 53.22% compared to longitudinally unstiffened plate girder. Comparison of the ultimate load of longitudinally stiffened and unstiffened plate girder are given in table 2. The use of slender longitudinal stiffener in plate girder improves the load-carrying capacity without adding much dead weight.

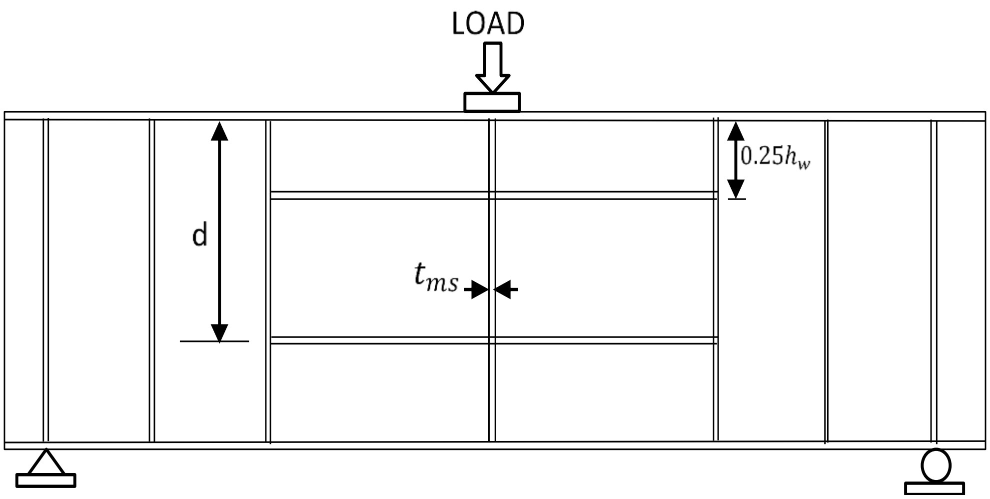


Figure 11. Plate girder with two longitudinal stiffener

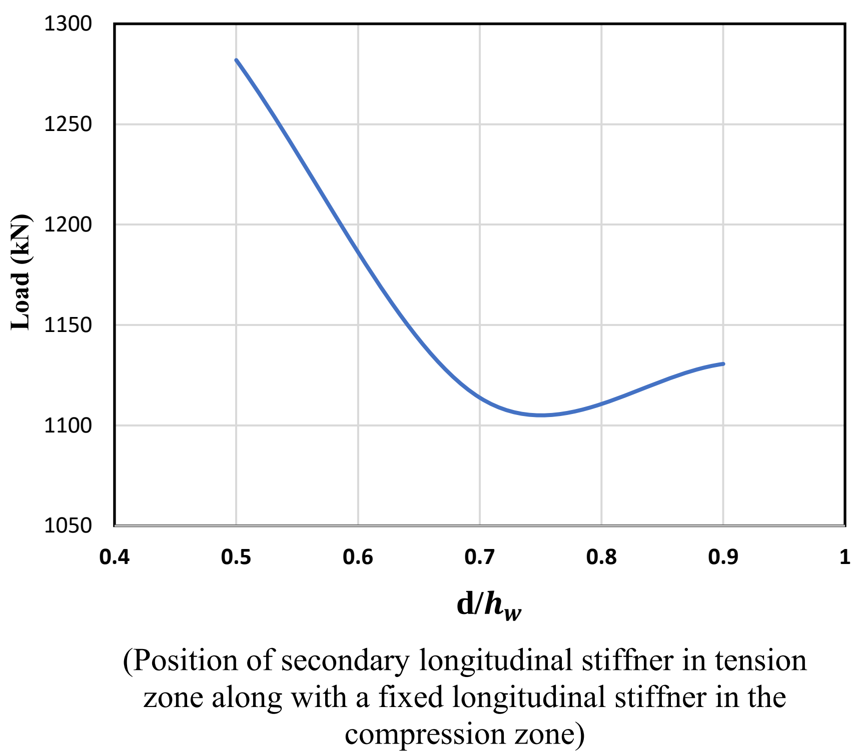


Figure 12. Combined effect of two longitudinal stiffener

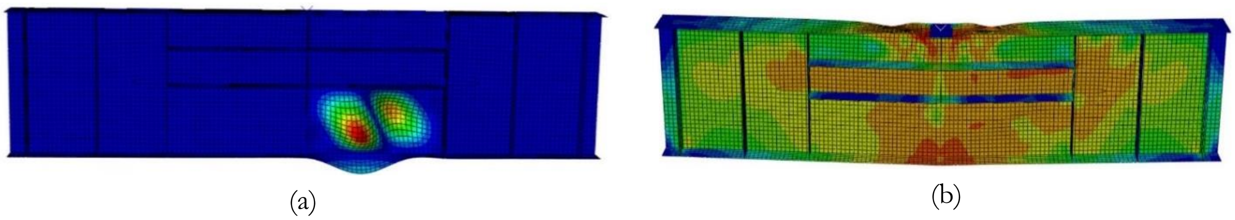


Figure 13. plate girder with two longitudinal stiffeners (a) Buckling mode shape (b) Failure mode

Table 2. Comparison of the ultimate load of longitudinally stiffened and unstiffened plate girder

Number of longitudinal stiffeners (at optimum location)	Ultimate load (kN)	Percentage increase in ultimate load (compared with longitudinally unstiffened plate girder)
unstiffened	835.97	-
1	1102.36	31.86%
2	1281.91	53.34%

3.2 Effect of web slenderness

Web slenderness is the main factor which controls the effect of a longitudinal stiffener. The effect of different stiffener locations was checked for different web slenderness values. The observations are shown in figure 14. The web slenderness values were varied from 75 to 200. The behaviour of plate girder with web slenderness greater than 100 was different from that of other plate girders with lower web slenderness (web slenderness ≤100). From the analysis, the optimum stiffener location ($0.25h_w$) identified in the previous section does not fit for long-span stainless steel plate girder with web slenderness less than 100.

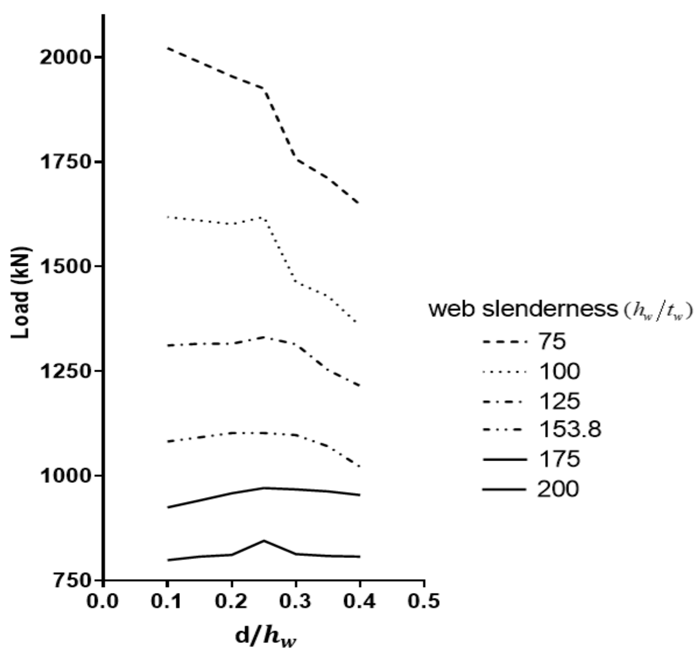


Figure 14. Effect of web slenderness

4 CONCLUSIONS

This numerical study investigated the effect of longitudinal stiffener on stainless steel plate girder under combined bending and shear. The finite element software ABAQUS was used for numerical modelling. The experiment conducted by Chen et al. [7] was used to validate the numerical model and then the parametric study was conducted. The following results were obtained.

- The longitudinal stiffener increases the load-carrying capacity of the long span stainless steel plate girder and improves the stability of the web plate by resisting lateral displacements.
- The optimum location for single longitudinal stiffener in slender stainless steel plate girder under combined bending and shear was found as 0.25 times the depth of web plate from the loaded flange.
- The presence of a single longitudinal stiffener at the optimum location ($0.25h_w$) results in 30.86 % increment in load-carrying capacity of long-span stainless plate girder compared to longitudinally unstiffened long span stainless steel plate girder.
- Most suitable location for the second longitudinal stiffener was observed at the neutral axis. The presence of two, longitudinal stiffener at optimum locations in tension zone long-span stainless steel plate girder increases the ultimate load by 53.34 % compared to longitudinally unstiffened plate girder.
- The optimum stiffener location ($0.25h_w$) was found suitable for plate girders with web slenderness greater than 100 only.

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