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Effect of Stiffeners on the Behavior of Slender Built up Steel I-Beams

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***Abstract*—**This paper presents the effect of stiffeners on the behavior of slender steel I-beams. Nonlinear three dimensional finite element models are developed to represent the stiffened steel I-beams. The well established finite element (ANSYS 13.0) program is used to simulate the geometric and material nonlinear nature of the problem. Verification is achieved by comparing the obtained numerical results with the results of previous published experimental work. The parameters considered in the analysis are the horizontal stiffener's position and the horizontal stiffener's dimensions as well as the number of vertical stiffeners. The studied dimensions of the horizontal stiffeners include the stiffener width, the stiffener thickness and the stiffener length. The results of the achieved numerical parametric study for slender steel I-beams show the significant effect of stiffeners on the beam behavior and its failure load.

***Keywords*—**Steel I-beams, local buckling, slender, stiffener, thin walled section.

I. Introduction

SLENDER steel plate girders are used in a variety of structural engineering applications, due to their high strength to weight ratios. The behavior of these slender girders has some problems of local buckling, lateral-torsional buckling and shear buckling. The use of slender steel plates stiffened with vertical stiffeners is suitable solution to eliminate the buckling problems. During the past four decades, numerous tests have been conducted on slender plate girders with and without stiffeners to provide a better understanding of the modes of failure and the influence of geometric and material parameters on their ultimate resistance. Ishac et al. [1], [2] presented a numerical study for slender plate girder without and with horizontal stiffeners at web-depth/5 measured from the compression flange and also illustrated experimental study for four slender steel I-beams. Saša Kovačević et al. [3] described the behavior of the longitudinally unstiffened web plate due to patch loading. Chacón R et al. [4] presented a numerical study for longitudinally stiffened steel plate girders subjected to patch loading. Alinia et al. [5] investigated the optimum location and dimensions of longitudinal stiffeners in web plates under in-plane bending using finite element method. Kövesdi et al. [7] presented analytical and numerical study for I-beam with horizontal stiffeners under the combined shear and patch loading. Graciano et al. [8] presented a review and nonlinear finite element analysis for three studied cases related to actual launched bridges. The influence of the longitudinal stiffener and girder depth on the capacity of girder under patch loading was concluded in the study [8]. The objective of this work is to provide an extensive numerical study to the behavior of slender built up steel I- beams showing the effect of using horizontal stiffener at different positions and different dimensions. To achieve this goal, a finite elements model is developed by using a commercial finite element program ANSYS 13.0 [6]. This model is used to conduct the parametric study required to fulfill the main research objective stated above.

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II. Numerical Analysis

A. Finite Element Model

A finite element model using a non-linear finite element program ANSYS 13.0 [6] is developed for simulating a simply supported steel slender plate girders. Among the elements used in the model is the shell 181 that is available in ANSYS library. This element is used efficiently for modeling the buckling problems. The mesh density is chosen so that the elements aspect ratio is nearly equal to one. The beams boundary conditions at supports are simulated to represent hinges where the degrees of freedom (DOFs) ux, uy and uz are constrained and for the roller supports where the DOFs uy and uz are constrained. Another element solid 186 is used to simulate the solid part at the supports and under the two point loads. Geometric imperfections are applied to the studied beams. Two cases are considered for modeling the material non-linearity, the perfect linear elastic and the multi linear elastic-plastic. The steel elastic modulus is taken as $1.9x10^5$ MPa and Poisson's ratio is assumed to be 0.3.

B. Verification of Results

The results obtained by the developed finite element model are checked against the results of previous experimental work [2]. This experimental work was conducted on four slender steel I-beams with and without horizontal stiffeners. The horizontal stiffener is located at web-depth/5 measured from the compression flange. The beams are restrained laterally against lateral torsional buckling. The results of the present

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numerical analysis give close failure loads to the previous experimental work as shown in Table I.

TABLE I
FINITE ELEMENT AGAINST EXPERIMENTAL WORK RESULTS

Girder	a/d_w	d_w/t_w	$b_f/2t_f$	V_{exp} (KN)	$V_{f.e}$ (KN)	$V_{f.e}$ / $V_{exp.}$
SP-1	1.833	115.38	15.625	385.6	358.25	.929
SP-2	1.833	115.38	15.625	505.3	502.64	.995
SP-3	1.375	153.84	15.625	440	474.5	1.078
SP-4	1.375	153.84	15.625	649.5	660.55	1.017

a= distance between vertical stiffeners, b_f= width of flange, d_w= depth of web, t_f= thickness of flange, t_w= thickness of web, V_{exp}= experimental failure load, V_{fe} =finite element failure load, $b_f/2t_f$= half flange width to thickness ratio, d_w/t_w= web depth to thickness ratio, a/d_w (aspect ratio) = distance between vertical stiffeners to web-depth ratio.

III. PARAMETRIC STUDY

A parametric study is carried out to investigate the effect of existence of horizontal stiffeners on the behavior and failure load of slender built-up steel I-beams. Different parameters are considered in this study. Among these parameters are the dimensions of the stiffener and its position along the beam section. The beams are loaded by two point loads at the two-thirds of the beam span as presented in Fig. 1. Two studied cases are considered in the analysis;

The first case is a beam with constant of web-depth (d_w=600 mm), web-thickness (t_w=5 mm), flange-width (b_f=150 mm), flange-thickness (t_f=5 mm) and beam-length (L=5400 mm). The variable parameters are presented in Table II. The beam sections are chosen to be a slender section with d_w/t_w =120 and $b_f/2t_f$ = 15.

TABLE II
CONSIDERED PARAMETERS FOR FIRST CASE STUDY

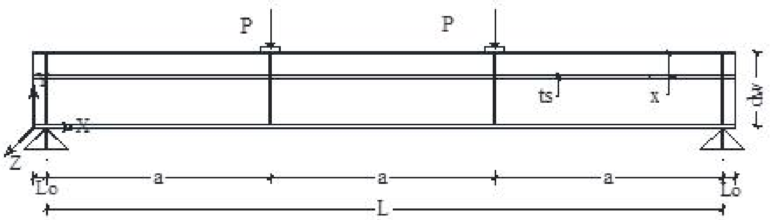
No.	Parameters	Status	values
1	Horizontal stiffener width (b_s)	Variable	55,65,75 mm
2	Horizontal stiffener thickness (t_s)	Variable	2,3,4,5,6 mm
3	Horizontal stiffener position (x/d_w)	Variable	0.15, 0.18, 0.2, 0.22, 0.24, 0.3
4	Aspect ratio (a/d_w)	Variable	3, 1.5, 1

x= distance between centerline of flange and center line of horizontal stiffener.

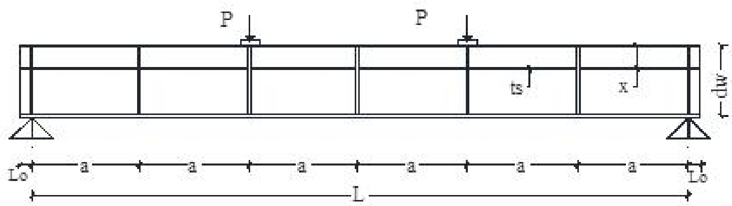
The second case is a beam with constant of web-depth (d_w=700 mm), web-thickness (t_w=5.83 mm), flange-width (b_f= 150 mm), flange-thickness (t_f=5 mm), beam-length (L=6300), horizontal stiffener's thickness (t_s = 5 mm) and aspect ratio (a/d_w = 3). The variable parameters are presented in Table III.

TABLE III
CONSIDERED PARAMETERS FOR SECOND CASE STUDY

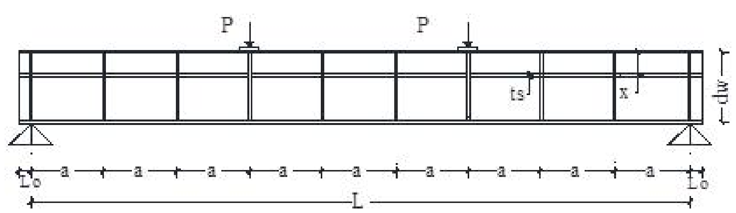
No.	Parameters	Status	values
1	Horizontal stiffener width (b_s)	variable	55,65,75 mm
2	Horizontal stiffener position (x/d_w)	variable	0.15, 0.18, 0.2, 0.22, 0.24,0.3



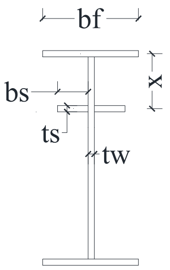
(a) Studied beams for a/d_w=3



(b) Studied beams for a/d_w=1.5



(c) Studied beams for a/d_w=1



(d) Cross section of studied beams

Fig. 1 Studied beams

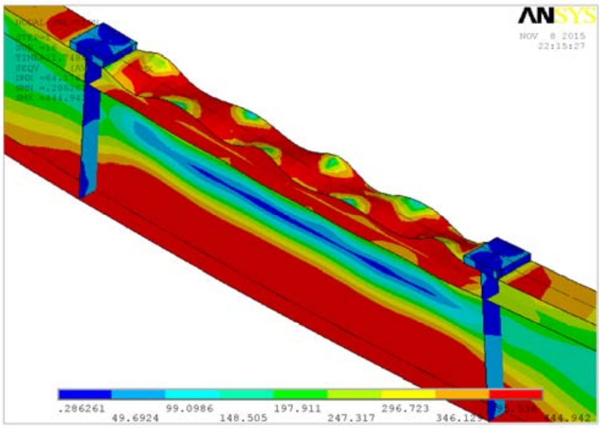


Fig. 2 Example of local buckling for stiffened slender plate beam

IV. Results and Discussions

Results of finite element analysis are shown in Figs. 3-37. The following sections illustrate respectively; the effect of horizontal stiffener's position (x/d_w), horizontal stiffener's thickness (t_s) and horizontal stiffener's width (b_s) for different aspect ratios (a/d_w=3, 1.5,1) beside studying the effect of horizontal stiffener's length (L_s) on the failure load ratio (P_f/P_s) of the analyzed beams where: P_F= failure load of stiffened beam and P_s= failure load of un-stiffened beam.

A. Effect of Horizontal Stiffener's Position

Figs. 3-5 show the effect of horizontal stiffener's position (x/d_w) on the beam failure load with different horizontal stiffener's width to thickness ratios (b_s/t_s) and for aspect ratio (a/d_w=3.0). Figs. 6-8 and 9-11 illustrate the same effect but for aspect ratios (a/d_w=1.5) and (a/d_w=1.0), respectively. All these results are for beams of the first study case (Table II).

Fig. 12 shows the effect of horizontal stiffener's position (x/d_w) on the beam failure load for different (bs/ts) in case of (ts=5 mm) and (a/d_w=3) for the second study case beams (Table III).

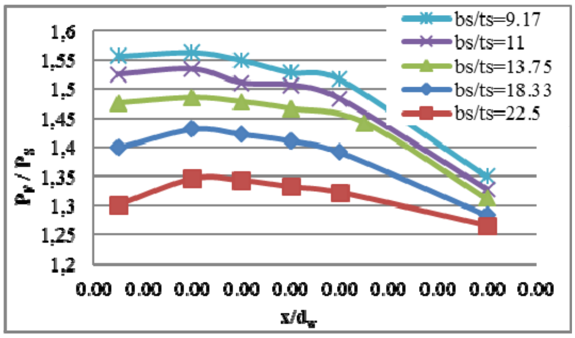


Fig. 3 Effect of (x/d_w) on the Failure Load (a/d_w =3.0 & b_s=55 mm)

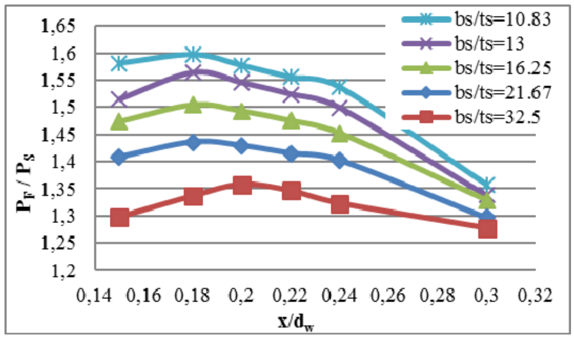


Fig. 4 Effect of (x/d_w) on the Failure Load (a/d_w =3.0 & b_s=65 mm)

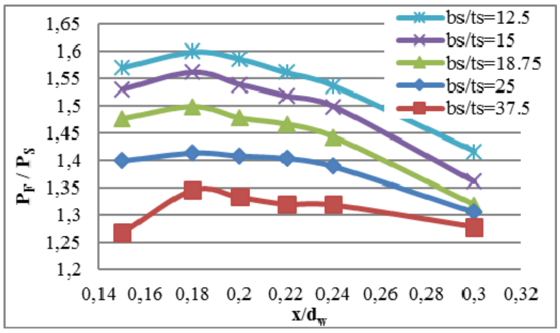


Fig. 5 Effect of (x/d_w) on the Failure Load (a/d_w =3.0 & b_s=75 mm)

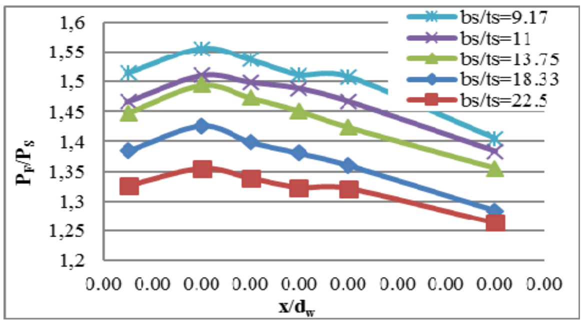


Fig. 6 Effect of (x/d_w) on the Failure Load (a/d_w =1.5 & b_s=55 mm)

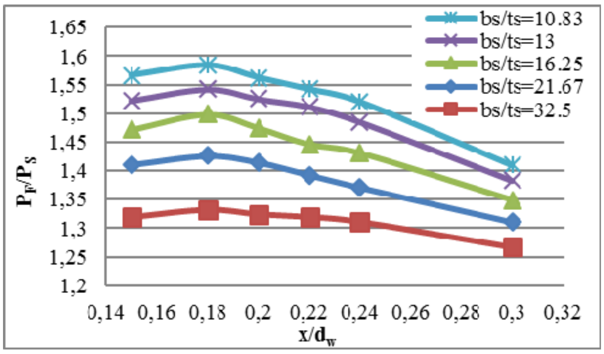


Fig. 7 Effect of (x/dw) on the Failure Load (a/dw =1.5 & bs=65 mm)

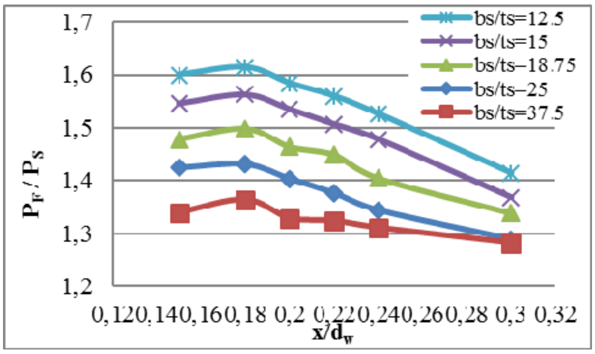


Fig. 11 Effect of (x/d_w) on the Failure Load (a/d_w =1.0 & b_s=75 mm)

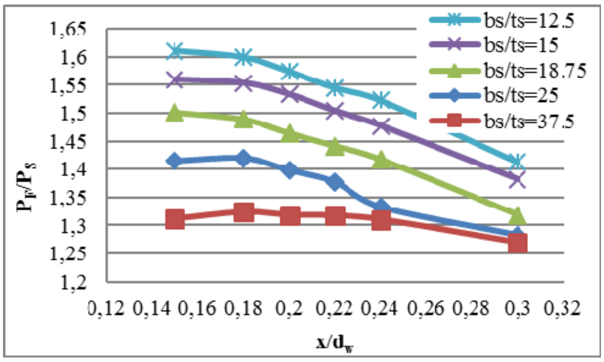


Fig. 8 Effect of (x/dw) on the Failure Load (a/dw =1.5 & bs=75 mm)

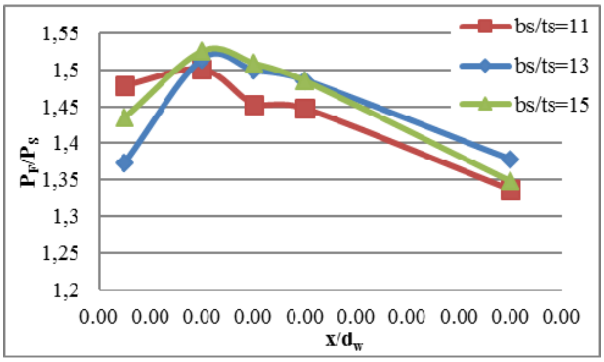


Fig. 12 Effect of (x/d_w) on the Failure Load (a/d_w =3.0 & t_s=5.0 mm)

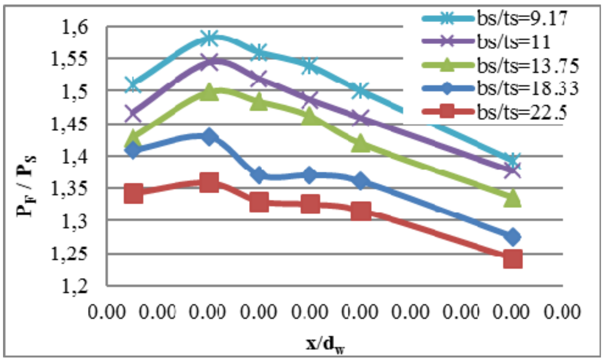


Fig. 9 Effect of (x/dw) on the Failure Load (a/dw =1.0 & bs=55 mm)

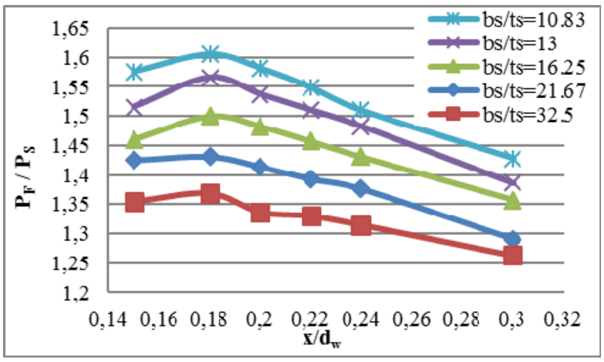


Fig. 10 Effect of (x/dw) on the Failure Load (a/dw =1.0 & bs=65 mm)

It is clear from these curves that, the optimum position of the horizontal stiffener (x/d_w) is about (0.18) of the web-depth measured from the compression flange. It is clear also that, as the thickness of the horizontal stiffener increases the beam failure load increases. The charts show that the load capacity of the stiffened beams is more than the load capacity of the un-stiffened ones reaching a ratio of 62%.

The illustrated figures highlight also that the aspect ratio has negligible effect on the results. This is because the failure mode is mainly due to local buckling in the compression flange.

B. Effect of Horizontal Stiffener's Thickness

In this section, the behavior of the beams in first case study (Table II) is investigated for different thicknesses of the horizontal stiffener (t_s). Figs. 13-15 present the effect of (t_s) on the beam failure load with change of the aspect ratio (a/d_w) and the stiffener's position (x/d_w). The stiffener width is taken to be (b_s=55 mm).

Figs. 16-18 show the effect of horizontal stiffener's thickness (t_s) on the failure load with change of (a/d_w), (x/d_w) and for (b_s=65mm).

Figs. 19-21 show the effect of horizontal stiffener's thickness (t_s) on the failure load with change of (a/d_w), (x/d_w) and for (b_s=75mm).

From all curves of this section, it is noticeable that increasing horizontal stiffeners' thickness (t_s) leads to increase the beam failure load. The increase in the beam failure load for t_s= 6 mm reaches to 60% of the un-stiffened beam for case of (x/d_w=0.18 and a/d_w =1.0) and in case of t_s= 2mm this percentage reaches to 37% for the same case.

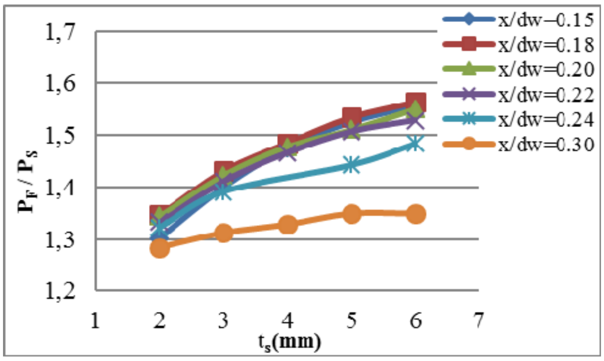


Fig. 13 Effect of (t_s) on the Failure Load(a/d_w =3.0 & b_s=55 mm)

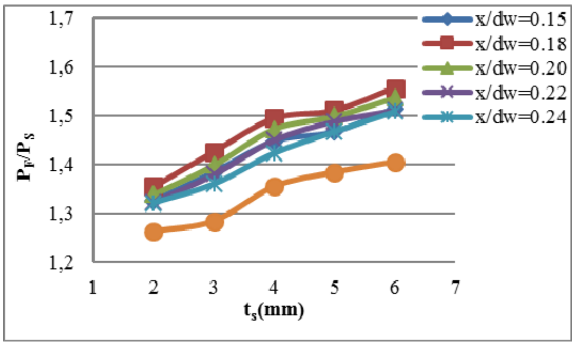


Fig. 14 Effect of (t_s) on the Failure Load(a/d_w =1.5 & b_s=55 mm)

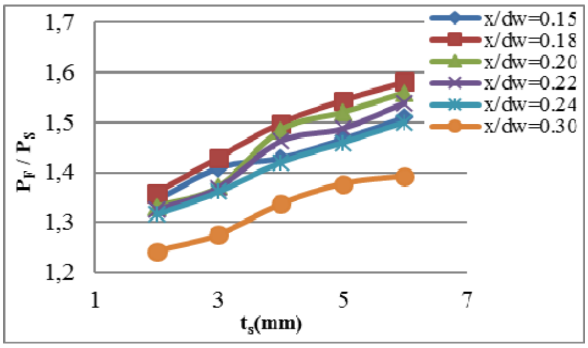


Fig. 15 Effect of (t_s) on the Failure Load (a/d_w =1.0 & b_s=55mm)

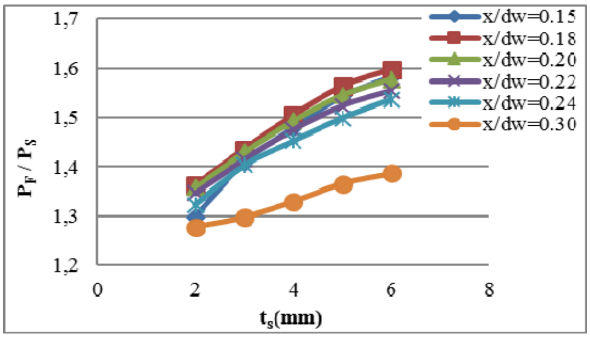


Fig. 16 Effect of (t_s) on the Failure Load (a/d_w=3.0 & b_s = 65 mm)

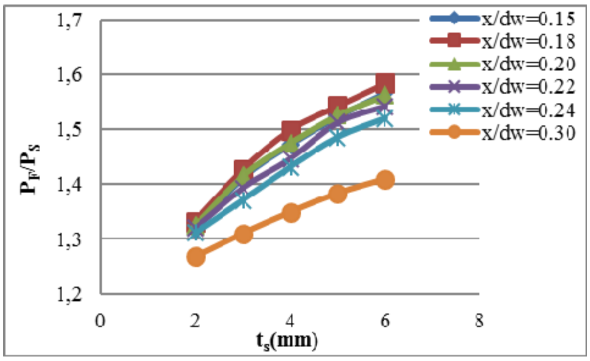


Fig. 17 Effect of (t_s) on the Failure Load (a/d_w=1.5 & b_s = 65 mm)

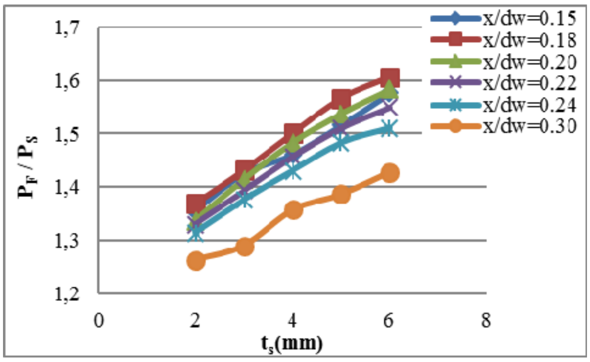


Fig. 18 Effect of (t_s) on the Failure Load (a/d_w=1.0 & b_s = 65 mm)

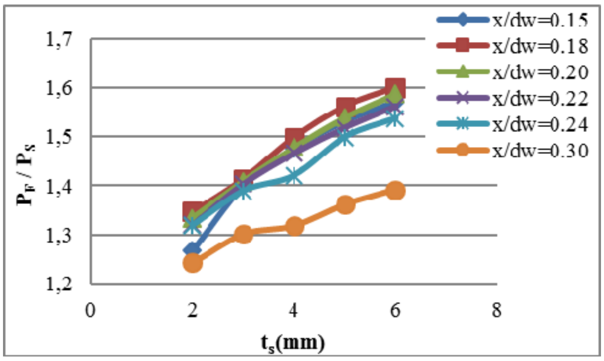


Fig. 19 Effect of (t_s) on the Failure Load (a/d_w=3.0 & b_s = 75 mm)

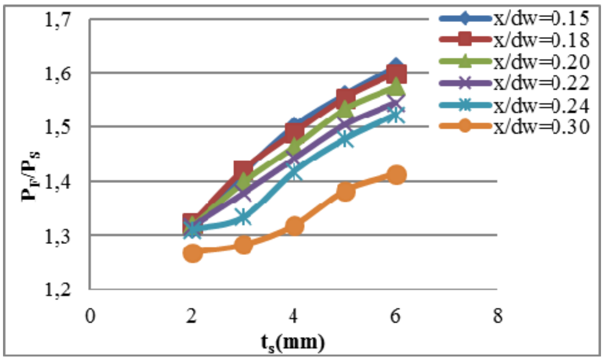


Fig. 20 Effect of (t_s) on the Failure Load (a/d_w=1.5 & b_s = 75 mm)

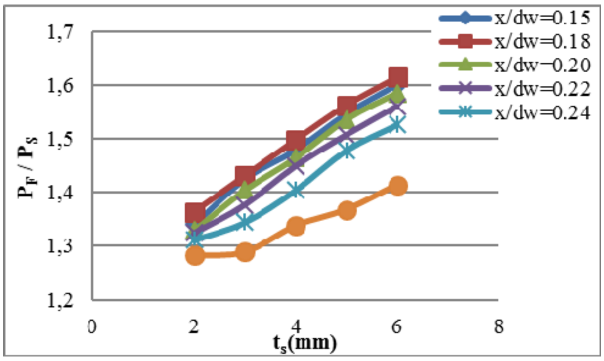


Fig. 21 Effect of (t_s) on the Failure Load (a/d_w=1.0 & b_s = 75 mm)

It is clear also from all the above curves that the envelope curve is for the position (x/d_w= 0.18). This confirms the previous conclusion that the optimum position of the horizontal stiffener is at (x/d_w=0.18).

C. Effect of Horizontal Stiffener's Width

This section deals with the effect of the width of the horizontal stiffener (b_s) on the failure load of the slender steel I-beams. Figs. 22-26 show the effect of (b_s) on the beam failure load with different (t_s), (x/d_w) and for (a/d_w=3.0).

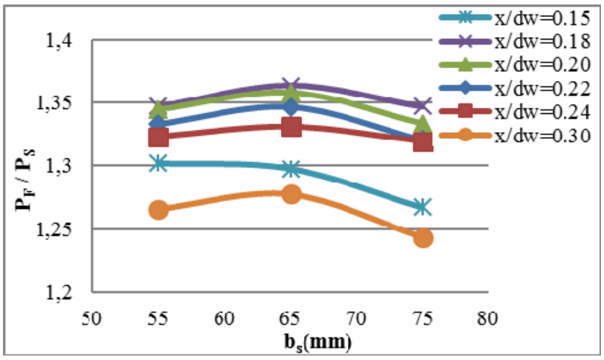


Fig. 22 Effect of (b_s) on the Failure Load (t_s = 2.0 mm & a/d_w=3.0)

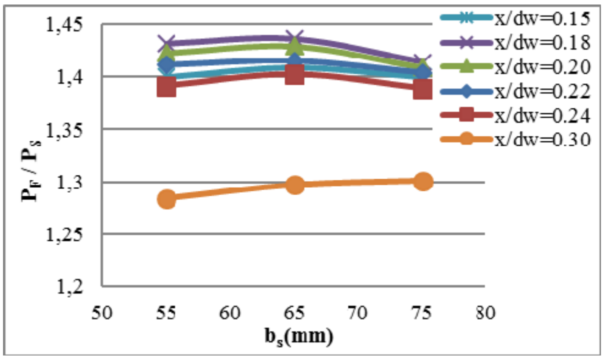


Fig. 23 Effect of (b_s) on the Failure Load (t_s = 3.0 mm & a/d_w=3.0)

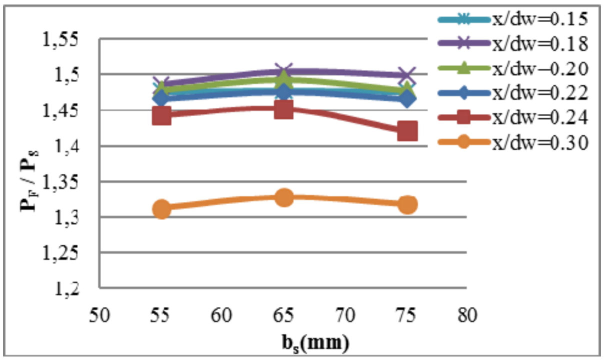


Fig. 24 Effect of (b_s) on the Failure Load (t_s = 4.0 mm & a/d_w=3.0)

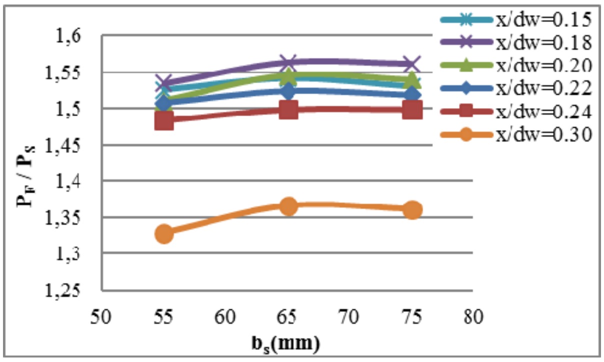


Fig. 25 Effect of (b_s) on the Failure Load (t_s = 5.0 mm & a/d_w=3.0)

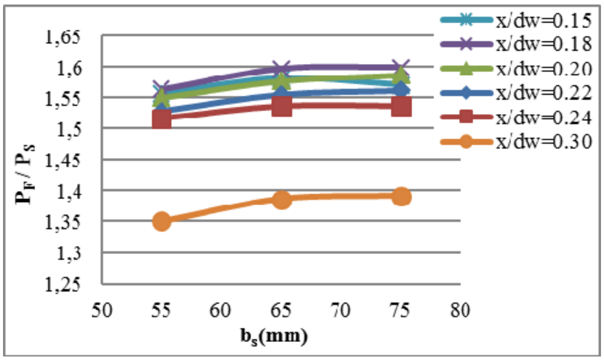


Fig. 26 Effect of (b_s) on the Failure Load (t_s = 6.0 mm & a/d_w=3.0)

Figs. 27-31 show effect of horizontal stiffener's width (b_s) on the failure load with change of (t_s), (x/d_w) and for (a/d_w=1.5). These charts illustrate that the beams with horizontal stiffener's width 65 mm give little improvement in the failure load with respect to the beams with horizontal stiffener's width 55.0 or 75.0 for all studied sections. For example, in Fig. 24, the increasing in failure load at bs= 65 mm reaches to 51% in case of (x/dw=0.18 and ts=4 mm), but at bs=75 mm it reaches to 50%, and at bs= 55 mm it reaches to 48% in the same case.

It is clear also from all the above curves that the envelope curve is for the position (x/d_w=0.18). This confirms the previous conclusion that the optimum position of the horizontal stiffener is at (x/d_w=0.18).

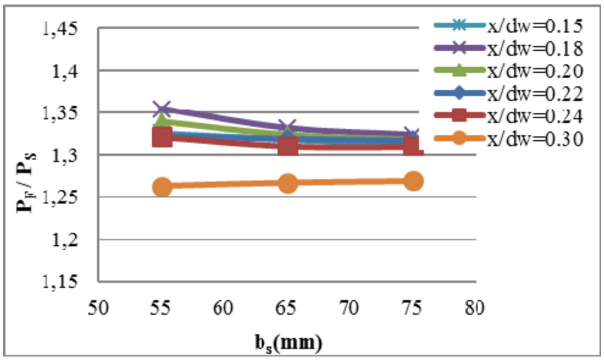


Fig. 27 Effect of (b_s) on the Failure Load (t_s = 2.0 mm & a/d_w=1.5)

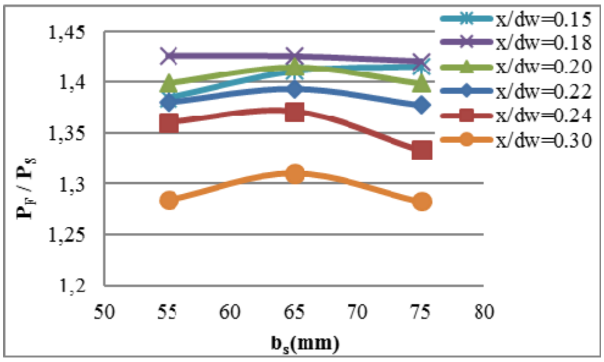


Fig. 28 Effect of (b_s) on the Failure Load (t_s = 3.0 mm & a/d_w=1.5)

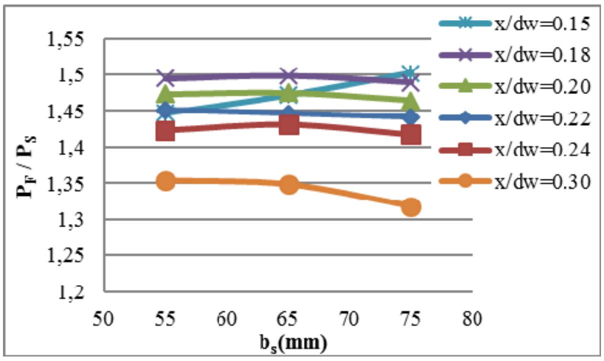


Fig. 29 Effect of (b_s) on the Failure Load if (t_s = 4.0 mm & a/d_w=1.5)

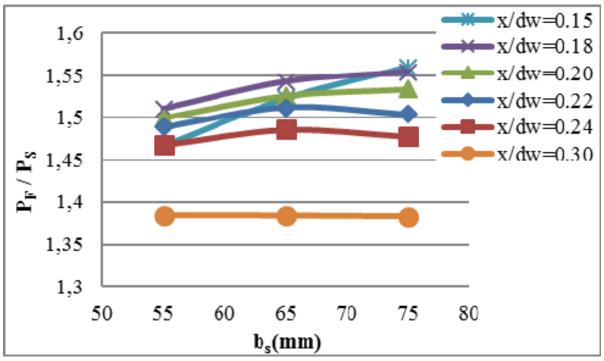


Fig. 30 Effect of (b_s) on the Failure Load (t_s = 5.0 mm & a/d_w=1.5)

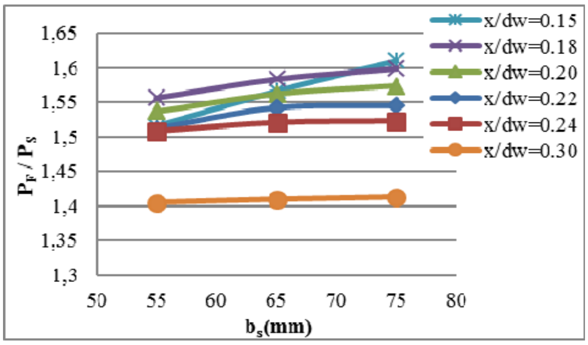


Fig. 31 Effect of (b_s) on the Failure Load (t_s = 6.0 mm & a/d_w=1.5)

Figs. 32-36 show effect of horizontal stiffener's width (b_s) on the failure load with change of (t_s), (x/d_w) and for (a/d_w=1.0).

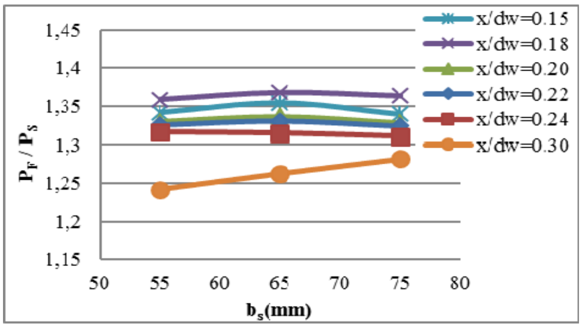


Fig. 32 Effect of (b_s) on the Failure Load (t_s =2.0 mm & a/d_w=1.0)

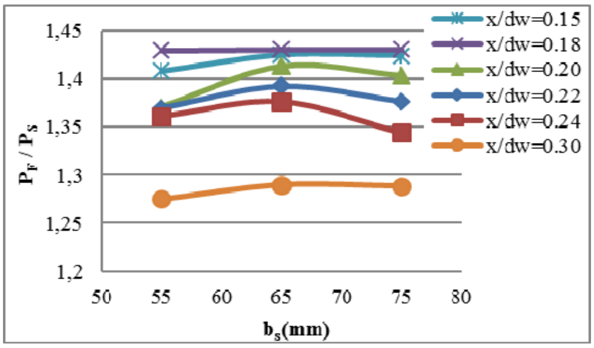


Fig. 33 Effect of (b_s) on the Failure Load (t_s =3.0 mm & a/d_w=1.0)

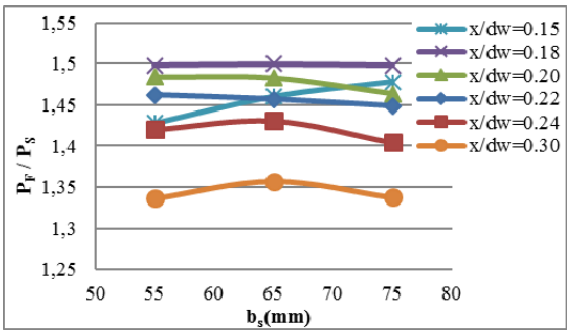


Fig. 34 Effect of (b_s) on the Failure Load (t_s =4.0 mm & a/d_w=1.0)

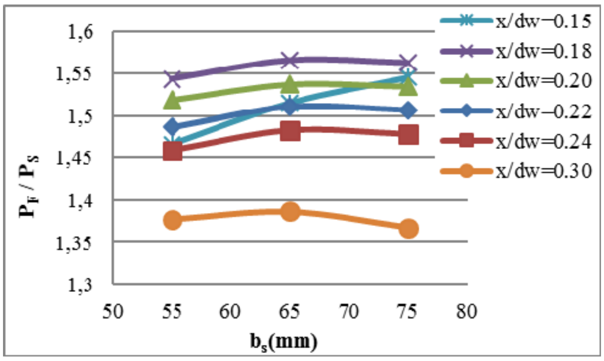


Fig. 35 Effect of (b_s) on the Failure Load (t_s =5.0 mm & a/d_w=1.0)

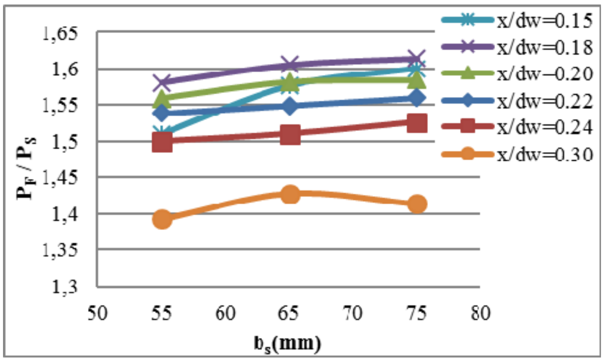


Fig. 36 Effect of (b_s) on the Failure Load (t_s =6.0 mm & a/d_w=1.0)

D.Effect of Horizontal Stiffener's Length

Figs. 37 and 38 show the effect of the length of horizontal stiffener (L_s) on the beam failure load for the first and the second studied cases respectively for t_s = 5.0 mm, b_s = 55.0 mm and a/d_w = 1.0.

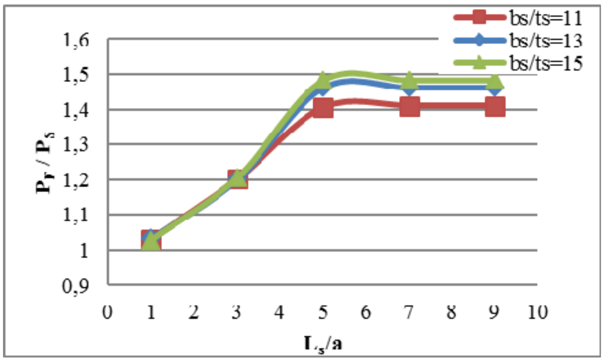


Fig. 37 Effect of (L_s) on the beam failure load for first study case (t_s = 5.0 mm & a/d_w = 1.0)

The two curves introduce that the increasing of horizontal stiffeners' length (L_s) increases the failure load of the beam until the length becomes 55% from the beam length (L). Then, the increasing of the stiffener length (L) above this limit has no effect on the beam failure load.

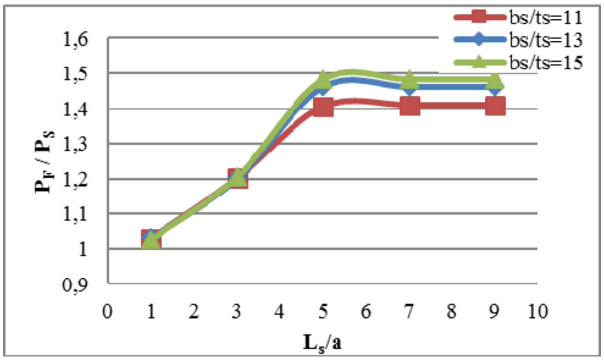


Fig. 38 Effect of (L_s) on the beam failure load for second study case (t_s = 5.0 mm & a/d_w = 1.0)

V. Summary and Conclusions

This study deals with the effect of stiffeners on the performance of the slender steel I-beams loaded by two point loads at the two thirds of the beam span. Finite element model and parametric study are developed to perform the desired analysis. The parameters considered in the numerical analysis are the horizontal stiffener's position, width, thickness and length. The number of vertical stiffeners is also considered in the variables. The main conclusions drawn from this work are:

(1) The failure mode is mainly due to local buckling in the compression flange; hence, the aspect ratio (the ratio of the horizontal distance between the vertical stiffeners to the web depth) has no effect on the results.

(2) Using horizontal stiffener in slender steel I-beams increases the failure load of the beam for all considered cases.

(3) For all studied cases, increasing the thickness of the horizontal stiffener for slender steel I-beams leads to increase the beam failure load. For instance, the use of horizontal stiffener with 2 mm thickness increases the beam failure load with a ratio reaching to 35% of the failure load of the non-stiffened one. If a 6 mm horizontal stiffener's thickness is used, this ratio reaches to 60% of the failure load of the non-stiffened beam.

(4) The appropriate selection of the horizontal stiffener location improves the failure load of the beam to the maximum. For slender steel I-beams, the optimum position of the horizontal stiffener is at about 0.18 of the web depth measured from the compression flange.

(5) The width of the horizontal stiffener has a little effect on the failure loads of the slender I-beams. The stiffener width gives the maximum failure load of these beams when this width reaches about 0.85 of the half flange width.

(6) Increasing horizontal stiffeners' length (L_s) in the middle of the beam increases the failure load of the beam until the length becomes 55% from the beam length (L). Increasing the stiffener length (L_s) above this limit has no effect on the beam failure load.

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