

Article

Numerical Study of the Effect of Out-of-Plane Distance in the Lateral Direction at the Mid-Span of a Steel Beam on the Sectional Moment Capacity

Ahmed Mohamed Sayed ^{1,*} , Nageh M. Ali ^{1,2}, Mishal H. Aljarbou ¹, Abdullah Alzlfawi ¹ , Salman Aldhobaib ¹, Hani Alanazi ¹  and Abdulmalik H. Altuwayjiri ¹ 

¹ Department of Civil and Environmental Engineering, College of Engineering, Majmaah University, Al Majmaah 11952, Saudi Arabia; nageh82@mu.edu.sa (N.M.A.); m.aljarbou@mu.edu.sa (M.H.A.); a.alzlfawi@mu.edu.sa (A.A.); s.aldhobaib@mu.edu.sa (S.A.); hm.alanazi@mu.edu.sa (H.A.); a.altuwayjiri@mu.edu.sa (A.H.A.)

² Department of Civil Engineering, College of Engineering, Assiut University, Assiut 71511, Egypt

* Correspondence: a.sayed@mu.edu.sa



Academic Editors: Fangxin Hu, Shujun Hu and Hai-Ting Li

Received: 12 December 2024

Revised: 13 January 2025

Accepted: 16 January 2025

Published: 18 January 2025

Citation: Sayed, A.M.; Ali, N.M.; Aljarbou, M.H.; Alzlfawi, A.; Aldhobaib, S.; Alanazi, H.; Altuwayjiri, A.H. Numerical Study of the Effect of Out-of-Plane Distance in the Lateral Direction at the Mid-Span of a Steel Beam on the Sectional Moment Capacity. *Buildings* **2025**, *15*, 283. <https://doi.org/10.3390/buildings15020283>

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: Steel I-beams may be subject to deviation from their normal path towards the lateral direction due to obstacles along their axis line. This deviation in the lateral direction, i.e., the out-of-plane distance, affects the behavior of the steel beams and may reduce their ultimate capacity. To obtain this effect, finite element modeling (FEM) was used to model these beams with and without an out-of-plane distance at the mid-span beam length with several different variables. These variables were the out-of-plane distance, cross-section dimensions, beam length, and steel yield stress. The reliability of using FEM simulation was confirmed by comparing the experimental test results of 25 available steel beams in previous studies. The results indicate the high accuracy of the simulation of this beam in terms of ultimate capacity, structural behavior, and deformation patterns. After verifying the results, 116 broad-flange I-beam (BFIB) steel beams with different out-of-plane distances were modeled. The results showed that using an out-of-plane distance equal to the flange width of the BFIB-300 cross-section caused a 60% decrease in the ultimate capacity. The reduction ratios in the ultimate moment capacity in out-of-plane steel beams were directly proportional to the out-of-plane distance, cross-sectional dimensions, and steel yield stress, while the beam length had no effect. Failure in beams containing an out-of-plane distance occurs as a result of a global buckling in the upper flange, which contains tensile stresses at the outer edge and compressive stresses at the inner edge, with stress concentration occurring at the point of contact of the out-of-plane part with the main beam. The prediction results of the design codes were compared with the results of experimental tests and the FEM analysis of the beams with and without out-of-plane distances. For all the beams with out-of-plane distances, all the design codes were unable to predict this ultimate capacity.

Keywords: BFIB steel beam; out-of-plane distance; sectional moment capacity; current design codes; finite element modeling

1. Introduction

Steel beams are the essential element when implementing covered areas or multi-story steel buildings. Normally, and in most cases, the axis of the steel beam in the longitudinal direction should be straight and in exactly one line. In some cases, such as the presence of irregular edges of the area to be covered or the presence of an obstacle in the longitudinal direction of the beam, a deviation occurs in the direction of its axis towards its lateral

direction, which is called an out-of-plane distance. This deviation can have a significant effect on the efficiency of steel beams and their ultimate bending moment capacity. Many previous studies have taken many variables into account when analyzing and monitoring the effectiveness of steel beams [1–4]. These steel beams have been studied under the influence of different types of loads, such as flexural loads [5–8] and shear loads [9–12], lateral torsional buckling [13–17], cyclic loads [18–21], and axial compression loads [22], or under the influence of temperature [23–25]. Saliba et al. [26] analyzed and compared the results of 34 steel beams collected from experimental tests and those available in previous studies and the predictions of different versions of Eurocode 3 [27,28]. The comparison results showed that EN 1993-1-4 [27] was conservative in predicting the steel beam capacities, while EN 1993-1-5 [28] was more accurate. The average ratios between the test results and the code predictions were 1.22 and 1.13 for EN 1993-1-4 [27] and EN 1993-1-5 [28], respectively, with a coefficient of variation, COV, equal to 14% and 11%, respectively. In general, all the prediction values from the codes were less than the actual capacity of the steel beams, meaning they all fell on the safe side of the design; this is consistent with the same result in [29,30]. Graciano [31] conducted experimental tests on steel beams using a longitudinal web stabilizer in the compression zone. The results showed that placing a longitudinal stabilizer at a distance equal to 0.3 from the height of the web of the beam increased the ultimate strength of the beam; however, if the distance of the longitudinal stabilizer exceeded 40 times the thickness of the web, this did not affect the efficiency of the steel beam. Others have studied the presence of damage, cuts, or openings in the cross-section of the steel beam, whether in the web or the flange [19,32–35]. Sayed [19] conducted a numerical study on steel beams with damage to the upper and lower flanges of the cross-section. The results indicated that the presence of any percentage of damage to the upper flange directly affected the efficiency and ultimate capacity of these steel beams. The presence of damage at percentages of the flange width equal to 10% and 40% on one side of the upper flange resulted in reductions in the ultimate bending moment capacity of the beam of 3.1% and 27.1%, respectively. When these ratios occurred from both sides of the upper flange, it caused reductions in capacity equal to 4.9% and 42.5%, respectively. As for the damage in the lower flange, no effect appeared until the damage percentage was equal to 30% of the width of the flange on both sides. Hou et al. [36] conducted experimental tests on seven steel beam specimens with a complete cut at the lower edge of the cross-section at the mid-length of the beam—a control beam—and used damage to the web at rates equal to 15% and 28% of the web height at the cut location at the lower edge. It was found that the damage in the steel beam web with flange cuts in the tension zone directly affected the efficiency and ultimate capacity. Meanwhile, the damage rates of 15% and 28% caused reductions in the ultimate load capacity by rates of 75.76% and 57.54%, respectively.

Recently, the use of finite element modeling (FEM) simulation has become essential in modeling structural elements, as it saves time, effort, and costs when implementing these elements compared to experimental tests. It is also possible to implement some structural elements that cannot be implemented through experimental tests due to the large size of the models, the presence of danger during some measurements, or the time required to implement these tests. For these reasons, researchers have tended to use FEM simulation and have measured the accuracy and reliability of the modeling of various structural elements under many factors, variables, and different loads [37–40]. FEM analysis was used in modeling steel beams with and without a corrugated web [41–44] and cold-formed sections [45–48]. Perera and Mahendran [49] carried out FEM analysis on six steel beams that had already been studied experimentally. The comparison results showed excellent agreement in the deformed shapes, moment–deflection relationship, and ultimate capacity,

with an average ratio of 1.03 with a COV of 2.0%. Tao et al. [50] performed FEM analysis on 340 specimens with different geometric dimensions and cross-sectional variations, where there were 44 rectangular, 142 circular, and 154 square sections of steel tubes. The results showed high accuracy with an average capacity ratio of 1.019 with a standard deviation of 0.072. This result is considered one of the most important conclusions due to the large number of specimens used in the verification. From all of this evidence, it is concluded that FEM simulation can model structural elements accurately and reliably to obtain different results in terms of behavior and ultimate capacity.

Due to the abnormal conditions in the implementation of steel I-beams, where there are deviations in the edges of the coverage area or there are obstacles in the longitudinal direction of the center line of the beam, there is a high probability that these beams will be implemented with an out-of-plane distance in the lateral direction of the beam axis. By reviewing the previous literature, it became clear that most of the factors and variables that can affect the behavior and efficiency of steel beams have been studied extensively, except for this type of steel beam, where there is an out-of-plane distance in the lateral direction of the beam length, whether by experimental study or numerical analysis. Perhaps the shortcoming in studying these steel beams with an out-of-plane distance was due to the lack of exposure of researchers or the engineering community to the implementation of this type of steel beam at the construction site, or it may have been due to uncertainty or a lack of knowledge of the extent of its impact on the efficiency of this type of structural elements. With the increasing need for change in the structural systems, whether already existing or new, especially regarding bridges in which the columns are made of reinforced concrete and the steel beams are of the simple support type, it is possible to be exposed to this type of steel beam with a deviation in the beam axis, which causes the presence of an out-of-plane distance during implementation. Here, the following question can be asked: Why conduct this study on steel beams with an out-of-plane distance? This study establishes the first basic principles for choosing between two methods: first, implementing such steel beams with an out-of-plane distance, taking into account the results that are obtained through this study; second, avoiding it and the consequences resulting from its use and using other solutions to treat this type of steel beam. This will only become clear after studying these steel beams with an out-of-plane distance.

Therefore, in this research, an FEM study is conducted on broad-flange I-beam (BFIB) steel beams with an out-of-plane distance in the lateral direction at the mid-span length under many variables that may affect the beam efficiency and behavior. These variables include out-of-plane distance, cross-section dimensions, beam length, and steel yield stress. To achieve the purpose of this study, it was divided into four main stages. The first stage is to verify the accuracy and reliability of using FEM modeling in the simulation of such types of structural elements by comparing the results of experimental tests of some available beams in previous studies with the results of FEM analysis in terms of ultimate capacity, structural behavior, and deformed shape. The second stage, after ensuring the reliability of the FEM analysis, is to conduct a simulation of BFIB steel beams with all the proposed variables to obtain the extent of their effect on the steel beam's efficiency and behavior. Third, these beam capacities are compared with the prediction results from current design codes [51,52] to determine the accuracy of their use in calculating the ultimate capacity of this type of steel beam. Fourth, an attempt is made to propose a new model that can take different variables into account to calculate the ultimate capacity of steel beams with out-of-plane distance.

2. Current Design Models

Many previous studies have presented new models or modified existing models to calculate the steel beam moment capacity to achieve the highest possible accuracy. These proposed new models are mostly based on existing design codes. By reviewing the previous studies, it became clear that most of the studies were concerned with ANSI/AISC 360-22 [51] and Eurocode-3 [52] in designing or comparing the results of experimental tests or FEM analysis. ANSI/AISC 360-22 provides models that can predict the ultimate bending moment capacity of steel beams with a value that is usually less than or equal to the actual ultimate capacity of the steel beam, i.e., the values are on the safe side of the design. In conducting the forecasting process, ANSI/AISC 360-22 relies on classifying the cross-sections of steel beams into three main categories: compact, noncompact, and slender. These classifications depend directly on the dimensions of the flange for the cross-section in terms of width and thickness, the dimensions of the beam web in terms of height and thickness, and the type of cross-section used to determine the appropriate limits for it. The ultimate capacity of the bending moment for steel beams can be calculated based on the critical classification of the cross-section categories in terms of the flange or web, as shown in the following equations:

For the beam web:

$$\left(\lambda = \frac{d_w}{t_w}\right) \leq (\lambda_P = 3.76 \sqrt{\frac{E}{f_y}}) \quad \text{for the compact category} \quad (1)$$

$$3.76 \sqrt{E/f_y} < \frac{d_w}{t_w} \leq 5.70 \sqrt{E/f_y} \quad \text{for the noncompact category} \quad (2)$$

$$\frac{d_w}{t_w} > (\lambda_r = 5.70 \sqrt{\frac{E}{f_y}}) \quad \text{for the slender category} \quad (3)$$

For the beam flange:

$$\left(\lambda = \frac{b}{t_f}\right) \leq (\lambda_P = 0.38 \sqrt{\frac{E}{f_y}}) \quad \text{for the compact category} \quad (4)$$

$$0.38 \sqrt{E/f_y} < b/t_f \leq 1.0 \sqrt{E/f_y} \quad \text{for the noncompact category} \quad (5)$$

$$b/t_f > (\lambda_r = 1.0 \sqrt{\frac{E}{f_y}}) \quad \text{for the slender category} \quad (6)$$

where d_w is beam web height, t_w is beam web thickness, t_f is flange thickness, $b = b_f/2$, b_f is total flange width, f_y is the steel yield stress, and E is the steel modulus of elasticity. After determining the category of the beam cross-section, the appropriate equation (Equations (7) to (9)) can be used to calculate the ultimate capacity of the bending moments.

$$M_P = f_y \times Z \quad \text{for the compact category} \quad (7)$$

$$M_{el} = M_P - (M_P - f_y \times S) \left(\frac{\lambda - \lambda_P}{\lambda_r - \lambda_P} \right) \leq M_P \quad \text{for the noncompact category} \quad (8)$$

$$M_{ef} = f_y \times S_{ef} \quad \text{for the slender category} \quad (9)$$

where M_P is the plastic moment capacity, M_{el} is the elastic moment capacity, M_{ef} is the effective moment capacity, Z is the plastic section modulus, S is the elastic section modulus, and S_{ef} is the effective section modulus.

As for Eurocode-3 [52], there are four design categories for the cross-section of the steel beam. These categories depend on the dimensions of the flange and the web of the cross-section in terms of the ratio between the width and thickness, the cross-section type, and the type of stresses affecting the section that determine the limits for each design category.

For the beam web:

$$\text{Class 1 : } \frac{d_w}{t_w} \leq 72 \sqrt{235/f_y} \quad (10)$$

$$\text{Class 2 : } 72 \sqrt{235/f_y} < \frac{b}{t_f} \leq 83 \sqrt{235/f_y} \quad (11)$$

$$\text{Class 3 : } 83 \sqrt{235/f_y} < \frac{d_w}{t_w} \leq 124 \sqrt{235/f_y} \quad (12)$$

$$\text{Class 4 : } \frac{d_w}{t_w} > 124 \sqrt{235/f_y} \quad (13)$$

For the beam flange:

$$\text{Class 1 : } \frac{b}{t_f} \leq 9 \sqrt{235/f_y} \quad (14)$$

$$\text{Class 2 : } 9 \sqrt{235/f_y} < \frac{b}{t_f} \leq 10 \sqrt{235/f_y} \quad (15)$$

$$\text{Class 3 : } 10 \sqrt{235/f_y} < \frac{b}{t_f} \leq 14 \sqrt{235/f_y} \quad (16)$$

$$\text{Class 4 : } \frac{b}{t_f} > 14 \sqrt{235/f_y} \quad (17)$$

Class-1 and Class-2 are similar to Equation (7), which uses a plastic section to calculate the ultimate beam moment capacity according to ANSI/AISC 360-22. In Class-4, the beam bending moment is calculated as in the previous Equation (9), while the elastic section in Equation (18) for Class-3 is used to calculate the ultimate beam moment capacity.

$$M_{el} = f_y \times S \quad (18)$$

3. Finite Element Model Study

3.1. Modeling and Characteristics of Steel Materials

To perform the FEM simulation of steel beams, ANSYS software (version 22) was used. To model the steel beams, the SOLID186 element [53] was used, as this element can simulate the different properties of the steel used in terms of large deflection, plasticity, higher strain capabilities, hyperelasticity, and creep. This element has 3-DOFs in the three directions with twenty points distributed at the vertices and midpoint of the element's perimeter. This element is suitable for asymmetric meshes and can model the deformations of elastic–plastic materials. To perform the simulation of these properties of the steel used, the relationship between stress and strain was obtained from the experimental results of axial tensile tests; in addition, the modulus of elasticity was determined, as reported in previous studies [54–57], and Poisson's ratio of 0.3 for steel was used. The stress–strain relationships and modulus of elasticity used in the simulation of the steel beams in the FEM modeling process are listed in Table 1.

Table 1. The relationship between stress and strain for steel applied to the FEM modeling.

Sayed and Alanazi [54]		Shi et al. [55]		Shokouhian and Shi [56]		Yang et al. [57]			
$f_y = 282 \text{ MPa}$		$f_y = 557 \text{ MPa}$		$f_y = 408.2 \text{ MPa}$		$f_y = 769 \text{ MPa}$		$f_y = 754 \text{ MPa}$	
Stress (MPa)	Strain	Stress (MPa)	Strain	Stress (MPa)	Strain	Stress (MPa)	Strain	Stress (MPa)	Strain
282	0.0013	557.00	0.0027	408.20	0.0021	769.00	0.0040	754.00	0.0039
291	0.0143	563.16	0.0063	414.13	0.0090	782.84	0.0128	767.86	0.0082
301	0.0279	570.51	0.0096	442.08	0.0180	787.86	0.0256	776.42	0.0126
317	0.0439	609.69	0.0199	474.90	0.0297	799.14	0.0352	780.99	0.0165
347	0.0825	640.44	0.0312	502.04	0.0430	811.14	0.0579	792.94	0.0279
369	0.1262	673.73	0.0491	526.75	0.0648	815.18	0.0823	800.38	0.0395
376	0.1543	693.70	0.0731	529.50	0.0934	816.00	0.0987	811.00	0.0718
377	0.1795	695.58	0.1079	527.00	0.1400	815.75	0.1125	799.24	0.1000
339	0.1946	687.32	0.1266	515.50	0.2200	807.91	0.1266	775.00	0.1168
299	0.2057	672.82	0.1428	481.00	0.2475	772.48	0.1487	747.88	0.1312
$E = 211 \text{ GPa}$		$E = 206 \text{ GPa}$		$E = 197.6 \text{ GPa}$		$E = 190.8 \text{ GPa}$		$E = 194.9 \text{ GPa}$	

3.2. Model Studies of Structure

Numerical analysis modeling was used to simulate 141 specimens of solid and flat-flange steel beams. These steel beams have many variables that directly affect their efficiency and ultimate load capacity. Two main groups were used for these samples, as follows:

The first group consists of 25 experimental test specimens of steel beams available in previous studies [56–60], as listed in Table 2. These beam specimens contain many variables, and each variable has a wide range of values applied in the experimental tests. Among these variables are the beam flange width, b_f , ranging from 159.15 to 271.00 mm; the flange thickness, t_f , ranging from 6.35 to 16.38 mm; the web beam height, d_w , ranging from 220.70 to 661.00 mm; the web thickness, t_w , ranging from 6.17 to 15.00 mm; and the steel yield stress used, f_y , varying from 408.2 to 886.00 MPa, in addition to the length of the steel beam, L , ranging from 1360 to 6000 mm. Some of these steel beam specimens were tested experimentally under the influence of three-point loading, as in [57,58,60], while others were tested under the influence of four-point loading, as in [55,56,59]. The loading was applied to the FME models by force control. All these specimens are collected from experimental tests and contain many variables and are primarily used to study the reliability and accuracy of using FEM simulation.

Through Equations (1) to (12), the design class classification of the steel beam sections collected from previous studies can be determined, as listed in Table 3. Through the geometric dimensions shown in Table 2, the sections were classified based on the critical condition in the design category, whether for the beam flange or the beam web. It is noted that most critical classifications follow the values resulting from the dimensions of the beam flange, whether for ANSI/AISC 360-22 [51] or Eurocode-3 [52] because the permissible limits for determining the section category for the flange have lower values than their counterparts for the beam web. Specimens were carefully selected to include all design categories based on the current design code classifications. For ANSI/AISC 360-22, there are specimens of the compact, noncompact, and slender categories, and for Eurocode-3 [52], there are the categories Class-1, Class-2, Class-3, and Class-4. This diversity of design categories provides a high degree of validation and reliability when comparing experimental test results to existing design code prediction results or when comparing them to FEM simulation results.

Table 2. Details of steel I-beams from previous studies used to verify FEM simulation.

FE Model Based on	Beam Specimens	Steel Beam Dimensions						f_{yf} (MPa)	f_{yw} (MPa)
		b_f (mm)	t_f (mm)	d_w (mm)	t_w (mm)	L (mm)	a (mm)		
Shi et al. [55]	I-460-1	167.8	13.87	520.9	11.96	3400	1000	557.0	510.5
	I-460-2	260.1	13.94	610.8	12.08	3400	1000	557.0	510.5
	I-890-3	166.5	6.35	661.0	6.17	2000	600	886.0	886.0
Saliba and Gardner [58]	I-600 × 200 × 12 × 10-1	200.1	12.4	599.2	10.2	1360	600	484.0	433.0
	I-600 × 200 × 12 × 8-2	199.8	12.3	600.0	8.4	2560	1200	484.0	431.0
	I-600 × 200 × 12 × 10-2	200.4	12.6	600.1	10.6	2560	1200	484.0	433.0
	I-600 × 200 × 12 × 15-2	200.1	15.3	599.0	15.0	2560	1200	484.0	564.0
Shokouhian and Shi [56]	C1	169.0	11.91	357.4	7.87	3399	1000	408.2	442.8
	C2	263.6	11.85	358.48	7.82	3401	1000	408.2	442.8
Yang et al. [57]	Y1-3	178.98	13.59	373.26	9.57	3500	1500	769.0	781.0
	Y2-3	197.47	13.63	372.44	9.63	3500	1500	769.0	781.0
	Y6-3	201.46	13.50	323.94	9.65	3500	1500	769.0	781.0
	Y8-3	159.95	16.10	319.15	9.64	3500	1500	754.0	781.0
	Y9-3	159.15	16.26	370.11	9.90	3500	1500	754.0	781.0
	Y10-3	177.81	16.03	369.95	9.81	3500	1500	754.0	781.0
	Y12-4	177.40	16.38	320.19	9.50	4000	1200	754.0	781.0
	Y13-4	159.34	16.35	368.8	9.68	4000	1200	754.0	781.0
	Y14-4	182.36	16.11	368.32	9.51	4000	1200	754.0	781.0
Beg and Hladnik [59]	B1	271.00	12.40	222.70	10.40	5000	1800	797.0	775
	C1	251.00	12.60	221.30	10.40	5000	1800	776.0	775
	D1	220.80	12.40	220.90	10.40	5000	1800	873.0	830
	E1	198.80	12.60	220.70	10.40	5000	1800	797.0	830
Xiong et al. [60]	C1	180.17	10.48	249.26	9.01	5000	2500	525.0	541.0
	C2	179.19	10.49	247.74	9.00	6000	3000	525.0	541.0
	C3	179.15	10.47	431.03	8.79	5000	2500	525.0	541.0

The second group consists of 116 broad-flange I-beam (BFIB) specimens containing several variables with out-of-plane distances in the mid-span lateral direction. These variables are the out-of-plane distance, the size of the cross-section, the length of the steel beam, and the steel yield stress. These beams were simulated in 19 basic models that differed based on the BFIB cross-section size, beam length, and steel yield stress, as listed in Table 4. Each model contained a standard specimen with no out-of-plane distance, and seven specimens with out-of-plane distances of 300, 400, 500, 600, 800, 1000, and 2000 mm in the lateral direction of the middle beam span, as shown in Figure 1. All the BFIB steel beams were tested under three-point loading to failure load using hinged point support, as shown in Figure 1. Ten 10 mm thick stiffener plates were used at the supports, quarter span, and load points. To implement the part of the out-of-plane distance, the same type of cross-section was used for implementing the main beam. The installation was conducted by connecting the upper and lower flanges with the corresponding flanges of the main beam at its beginning and end. The entire height of the web out-of-plane part was also connected with the web of the main beam, as shown in Figure 1. This interconnection was performed by perfectly bonding all the available points in the mesh division. The value of the out-of-plane distance from the middle of the main beam flange of the two separate parts was also determined. To obtain the true effect of all the variables on these beams with an out-of-plane distance, these geometric dimensions were chosen to resemble those actually used in reality.

Table 3. Compactness classification of steel beam cross-section from previous studies.

FE Model Based on	Beam Specimens	ANSI/AISC 360-22 [51]			Eurocode-3 [52]		
		Flange	Web	Section	Flange	Web	Section
Shi et al. [55]	I-460-1	C	C	C	Class-1	Class-1	Class-1
	I-460-2	NC	C	NC	Class-3	Class-2	Class-3
	I-890-3	NC	S	S	Class-4	Class-4	Class-4
Saliba and Gardner [58]	I-600 × 200 × 12 × 10-1	NC	C	NC	Class-3	Class-2	Class-3
	I-600 × 200 × 12 × 8-2	NC	C	NC	Class-3	Class-3	Class-3
	I-600 × 200 × 12 × 10-2	NC	C	NC	Class-3	Class-2	Class-3
	I-600 × 200 × 12 × 15-2	C	C	C	Class-2	Class-1	Class-2
Shokouhian and Shi [56]	C1	C	C	C	Class-2	Class-1	Class-2
	C2	NC	C	NC	Class-4	Class-1	Class-4
Yang et al. [57]	Y1-3	NC	C	NC	Class-3	Class-1	Class-3
	Y2-3	NC	C	NC	Class-3	Class-1	Class-3
	Y6-3	NC	C	NC	Class-3	Class-1	Class-3
	Y8-3	C	C	C	Class-1	Class-1	Class-1
	Y9-3	C	C	C	Class-1	Class-1	Class-1
	Y10-3	C	C	C	Class-2	Class-1	Class-2
	Y12-4	C	C	C	Class-2	Class-1	Class-2
	Y13-4	C	C	C	Class-1	Class-1	Class-1
	Y14-4	C	C	C	Class-2	Class-1	Class-2
Beg and Hladnik [59]	B1	NC	C	NC	Class-4	Class-1	Class-4
	C1	NC	C	NC	Class-4	Class-1	Class-4
	D1	NC	C	NC	Class-4	Class-1	Class-4
	E1	NC	C	NC	Class-4	Class-1	Class-4
Xiong et al. [60]	C1	NC	C	NC	Class-3	Class-1	Class-3
	C2	NC	C	NC	Class-3	Class-1	Class-3
	C3	NC	C	NC	Class-3	Class-2	Class-3

Note: C = compact; NC = noncompact; S = slender.

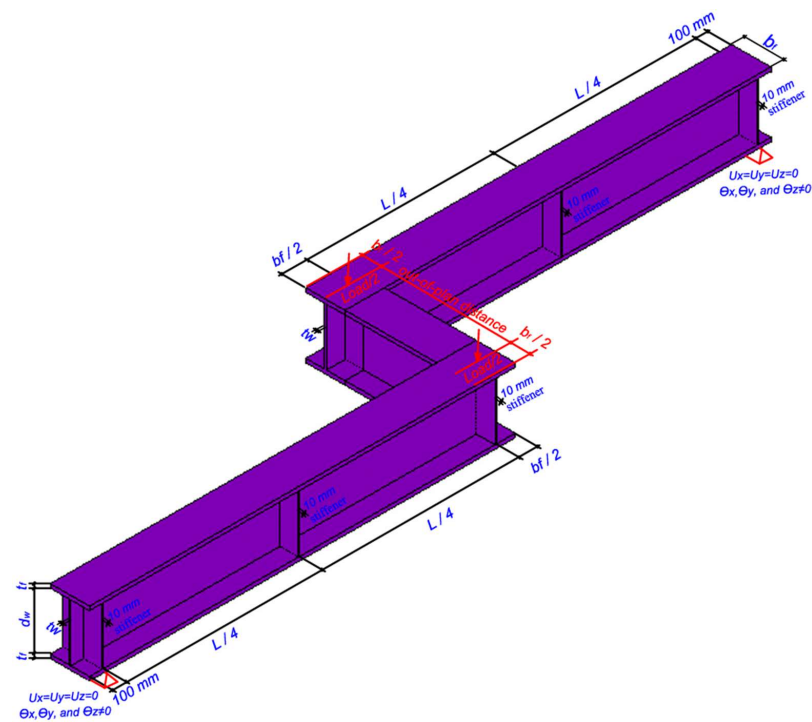
**Figure 1.** Boundary conditions and geometric details of the steel I-beams and out-of-plane distance used in FEM simulation.

Table 4. Details of the steel I-beams created in this study by FEM simulation.

Beam Specimens	Steel Beam Cross-Section Dimensions (mm)						f_y (MPa)	Cases of Out-of-Plane Distance, OOP, (mm)						
	b_f	t_f	d_w	t_w	L	a		1	2	3	4	5	6	7
BFIB500-L10-Fy282	300	30	440	16	10,000	5000	282	300	400	500	600	800	1000	2000
BFIB500-L9-Fy282	300	30	440	16	9000	4500	282	300	400	500	600	800	1000	2000
BFIB500-L8-Fy282	300	30	440	16	8000	4000	282	300	400	500	600	800	1000	2000
BFIB500-L6-Fy282	300	30	440	16	6000	3000	282	300	400	500	600	800	1000	2000
BFIB300-L10-Fy282	300	20	276	12	10,000	5000	282	300	400	500	600	800	1000	2000
BFIB300-L9-Fy282	300	20	276	12	9000	4500	282	300	400	500	---	---	---	---
BFIB300-L8-Fy282	300	20	276	12	8000	4000	282	300	400	500	---	---	---	---
BFIB300-L6-Fy282	300	20	276	12	6000	3000	282	300	400	500	---	---	---	---
BFIB400-L10-Fy282	300	26	348	14	10,000	5000	282	300	400	500	600	800	1000	2000
BFIB400-L9-Fy282	300	26	348	14	9000	4500	282	300	400	500	---	---	---	---
BFIB400-L8-Fy282	300	26	348	14	8000	4000	282	300	400	500	---	---	---	---
BFIB400-L6-Fy282	300	26	348	14	6000	3000	282	300	400	500	---	---	---	---
BFIB600-L10-Fy282	300	32	536	17	10,000	5000	282	300	400	500	600	800	1000	2000
BFIB600-L9-Fy282	300	32	536	17	9000	4500	282	300	400	500	---	---	---	---
BFIB600-L8-Fy282	300	32	536	17	8000	4000	282	300	400	500	---	---	---	---
BFIB600-L6-Fy282	300	32	536	17	6000	3000	282	300	400	500	---	---	---	---
BFIB500-L10-fy408	300	30	440	16	10,000	5000	408	300	400	500	600	800	1000	2000
BFIB500-L10-fy557	300	30	440	16	10,000	5000	557	300	400	500	600	800	1000	2000
BFIB500-L10-fy769	300	30	440	16	10,000	5000	769	300	400	500	600	800	1000	2000

3.3. Selection of the Optimal Mesh Size for Element Convergence

The sensitivity and convergence of the element mesh size dimensions play an effective and important role in the accuracy and results of the FEM analysis, as does the time required to perform the numerical analysis process. Therefore, the accuracy and convergence of the optimal mesh were tested by conducting five experiments on the largest specimen with the longest length equal to 6000 mm, where C2 was available from previous studies, including that by Xiong et al. [60]. Different trials were made by changing the dimensions of the mesh element size in terms of height, width, and length, respectively, where trial 1 had dimensions of $10 \times 10 \times 50$ mm, trial 2 had dimensions of $10 \times 10 \times 20$ mm, trial 3 had dimensions of $10 \times 10 \times 10$ mm, trial 4 had dimensions of $5 \times 5 \times 20$ mm, and trial 5 had dimensions of $5 \times 5 \times 10$ mm. In each trial, the ratio between the maximum bending moment resulting from the FEM analysis process and its corresponding value from the experimental test ($M_{u,FEM}/M_{u,Exp}$) was found. The relationship between each experiment and its corresponding measured ratio was plotted to determine the optimal size of the mesh elements, as shown in Figure 2. From the figure, it is clear that the optimal size of the mesh dimensions was $5 \times 5 \times 20$ mm in height, width, and length, respectively, as it gave the best possible accuracy for the FEM results and gave the best time required to conduct the FEM analysis process. Therefore, these dimensions were adopted in conducting the remaining FEM analysis processes for all the specimens, whether from previous studies or those proposed in this study.

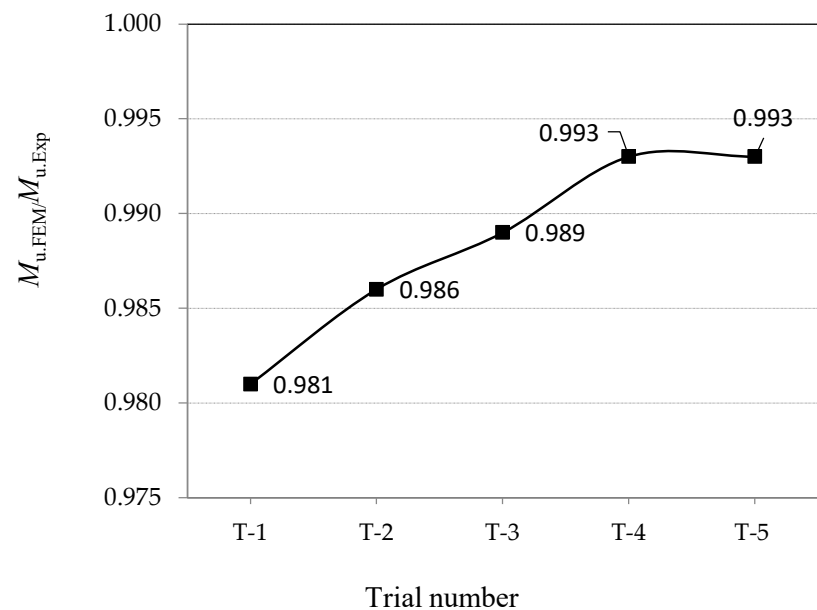


Figure 2. The relationship between the size of the mesh dimensions and the accuracy ratio in the ultimate bending moments.

4. Verifying Results from FEM Modeling and Current Design Codes

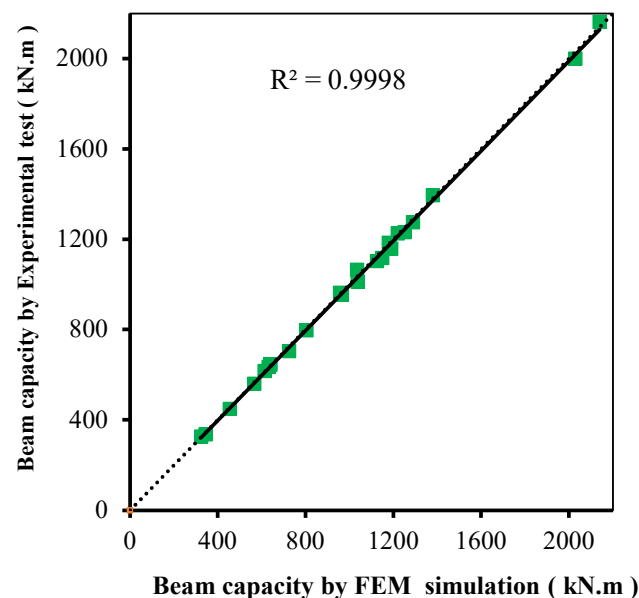
4.1. Verifying Results from FEM

The values of the steel beam moment capacities resulting from the experimental tests included in the previous studies [55–60] and the results of the FEM simulation of the same beams were compared. The process of comparing these results is the basic element for relying on the results and reliability of the FEM simulation in modeling these types of structural elements, as shown in Table 5 and Figure 3. Since these specimens contain many variables with a wide range of data and different design categories according to the classification of the current design codes, the accuracy and reliability of the modeling are demonstrated by the FEM analysis of these steel beams. By comparing the ratios between the steel beam capacity resulting from the FEM modeling and the experimental test results, the average of the ratios $M_{u,FEM}/M_{u,Exp}$ was found to be equal to 1.007, with a coefficient of correlation, r , equal to 0.999 and a coefficient of variation, COV, equal to 1.573%. Through these values, the use of the FEM modeling in simulating these types of steel beams is characterized by high accuracy and strong reliability in predicting the steel beam capacity. This result is consistent with many previous studies [30,49,50] when comparing the results of experimental tests with the results of FEM simulations.

An important element that demonstrates the accuracy of FEM simulations is the relationship between the applied moments and the corresponding mid-span deflection. Therefore, the beam bending moment and deflection relationship was obtained for six specimens with different variables included in previous studies, in which there were three steel beam specimens from Shi et al. [55] and three specimens from Saliba and Gardner [58]. The relationship resulting from the FEM simulation of the same steel beams mentioned above was determined, as shown in Figure 4. Figure 4 shows the accuracy and reliability of FEM simulation in modeling these steel beams, where the consistency between the relationships is excellent, and this result is consistent with many previous studies [26,29,49].

Table 5. Comparison of existing design codes and FEM results for steel I-beams with experimental test results.

FE Model Based on	Beam Specimens	$M_{u \cdot \text{Exp}}$ (kN.m)	FEM Results		Eurocode-3		ANSI/AISC 360-22	
			$M_{u \cdot \text{FEM}}$ (kN.m)	$M_{u \cdot \text{FEM}} / M_{u \cdot \text{Exp}}$	M_{EC3} (kN.m)	$M_{\text{EC3}} / M_{u \cdot \text{Exp}}$	M_{AISC} (kN.m)	$M_{\text{AISC}} / M_{u \cdot \text{Exp}}$
Shi et al. [55]	I-460-1	1225.40	1220.71	0.996	1107.42	0.904	1107.42	0.904
	I-460-2	1999.70	2029.06	1.015	1634.49	0.817	1802.57	0.901
	I-890-3	797.10	804.00	1.009	778.91	0.977	778.91	0.977
Saliba and Gardner [58]	I-600 × 200 × 12 × 10-1	1102.80	1126.05	1.021	1003.66	0.910	1054.88	0.957
	I-600 × 200 × 12 × 8-2	1172.00	1184.33	1.011	948.38	0.809	1053.68	0.899
	I-600 × 200 × 12 × 10-2	1395.00	1380.12	0.989	1029.32	0.738	1163.15	0.834
	I-600 × 200 × 12 × 15-2	2162.00	2139.76	0.990	1669.12	0.772	1669.12	0.772
Shokouhian and Shi [56]	C1	447.91	455.66	1.017	414.72	0.926	414.72	0.926
	C2	616.70	613.08	0.994	502.49	0.815	572.10	0.928
Yang et al. [57]	Y1-3	1012.23	1037.91	1.025	858.61	0.848	976.23	0.964
	Y2-3	1117.22	1149.06	1.028	931.68	0.834	1043.37	0.934
	Y6-3	962.23	957.55	0.995	798.76	0.830	887.64	0.922
	Y8-3	955.01	964.44	1.010	842.67	0.882	842.67	0.882
	Y9-3	1158.33	1191.08	1.028	1018.66	0.879	1018.66	0.879
	Y10-3	1230.55	1251.79	1.017	1091.67	0.887	1091.67	0.887
	Y12-4	1065.00	1034.81	0.972	927.58	0.871	927.58	0.871
	Y13-4	1184.36	1179.61	0.996	1013.63	0.856	1013.63	0.856
	Y14-4	1274.40	1290.05	1.012	1103.45	0.866	1103.45	0.866
Beg and Hladnik [59]	B1	703.80	724.61	1.030	515.43	0.732	670.31	0.952
	C1	646.20	640.70	0.991	506.92	0.784	614.36	0.951
	D1	644.40	638.66	0.991	518.41	0.804	620.38	0.963
	E1	559.80	567.00	1.013	502.72	0.898	515.72	0.921
Xiong et al. [60]	C1	335.3	344.88	1.029	292.81	0.873	313.81	0.936
	C2	326.39	324.12	0.993	289.58	0.887	301.58	0.924
	C5	634.68	631.40	0.995	561.05	0.884	574.05	0.904

**Figure 3.** Comparison of FEM results with experimental test results from previous studies.

The same steel beams from the previous studies that were used to compare the moment-to-deflection relationship [55,58] were used to compare the deformation shapes and failure locations with the FEM simulations, as shown in Figure 5. This comparison is important and complementary to the process of studying the reliability of simulation

using FEM analysis. From the deformation shapes and their locations, it became clear that the cause of the failure was a local buckling in the upper flange of the cross-section of the steel beam. This buckling occurs at the distance between the loading points when using the four-point loading system or near the applied loading point in the case when the three-point loading system is used; it was measured in both the experimental test and the FEM simulation results. The results of this comparison show the accuracy and reliability of the FEM simulation in modeling these steel beams, as there is an excellent match. This result is consistent with previous studies, such as those of Sayed and Al-Jarbou [29] and Perera and Mahendran [49].

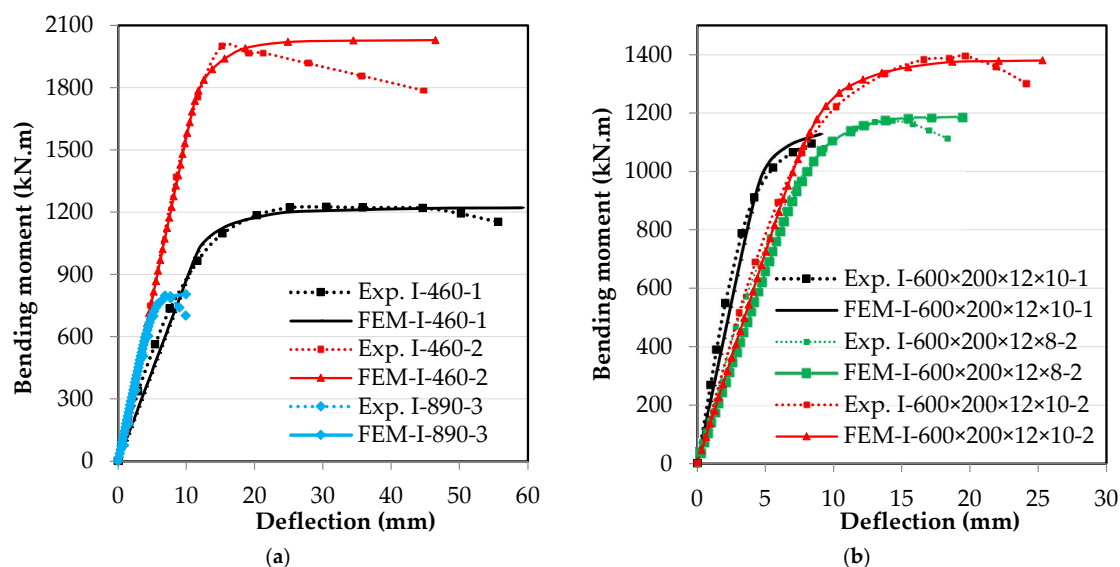


Figure 4. The beam bending moment and corresponding deflection relationships were obtained from FEM results and experimental tests. (a) Steel I-beam from Shi et al. [55]. (b) Steel I-beam from Saliba and Gardner [58].

4.2. Verifying Results from Current Design Codes

By reviewing the previous studies, it is found that most of them use the current codes Eurocode-3 and ANSI/AISC 360-22 in the comparison process. This is because these codes are the basic element for building the rest of the proposed design models to predict the beam capacities. Through the available Equations (1) to (10) and the classification of the obtained design categories, as shown in Table 3, the predicted values of the steel beam moment capacity were calculated, as listed in Table 5. Through the table, the relationship between the ultimate beam capacity resulting from the prediction of the design codes and the ultimate capacity of the same beams resulting from the experimental tests was determined, as shown in Figure 6. From Table 5 and Figure 6, it is clear that the predictions of the current design codes [51,52] apply completely when the design classification of the steel beam cross-section is a compact category for ANSI/AISC 360-22 and with the Class-1 and Class-2 classifications of Eurocode 3. The difference in prediction values occurs when the classification is a noncompact category for ANSI/AISC 360-22 and a Class-3 classification for Eurocode 3, while the conformity returns if the classification is a slender category for ANSI/AISC 360-22 and a Class-4 classification for Eurocode 3. From Figure 6, all the values predicted from the current design codes [51,52] are less than the actual ultimate moment capacity resulting from the experimental tests of steel beams. This result is consistent with Sayed and Aljarbou [29] and Perera and Mahendran [30]. According to ANSI/AISC 360-22, the beam moment capacity can be predicted with an average $M_{AISC}/M_{u,Exp}$ ratio of 0.908, with an r of 0.998 and a COV of 5.12%. As for Eurocode-3, it can be predicted with an

average $M_{EC3}/M_{u,Exp}$ ratio of 0.851, with an r of 0.997 and a COV of 6.84%. All these results are for steel beams without any out-of-plane distances.

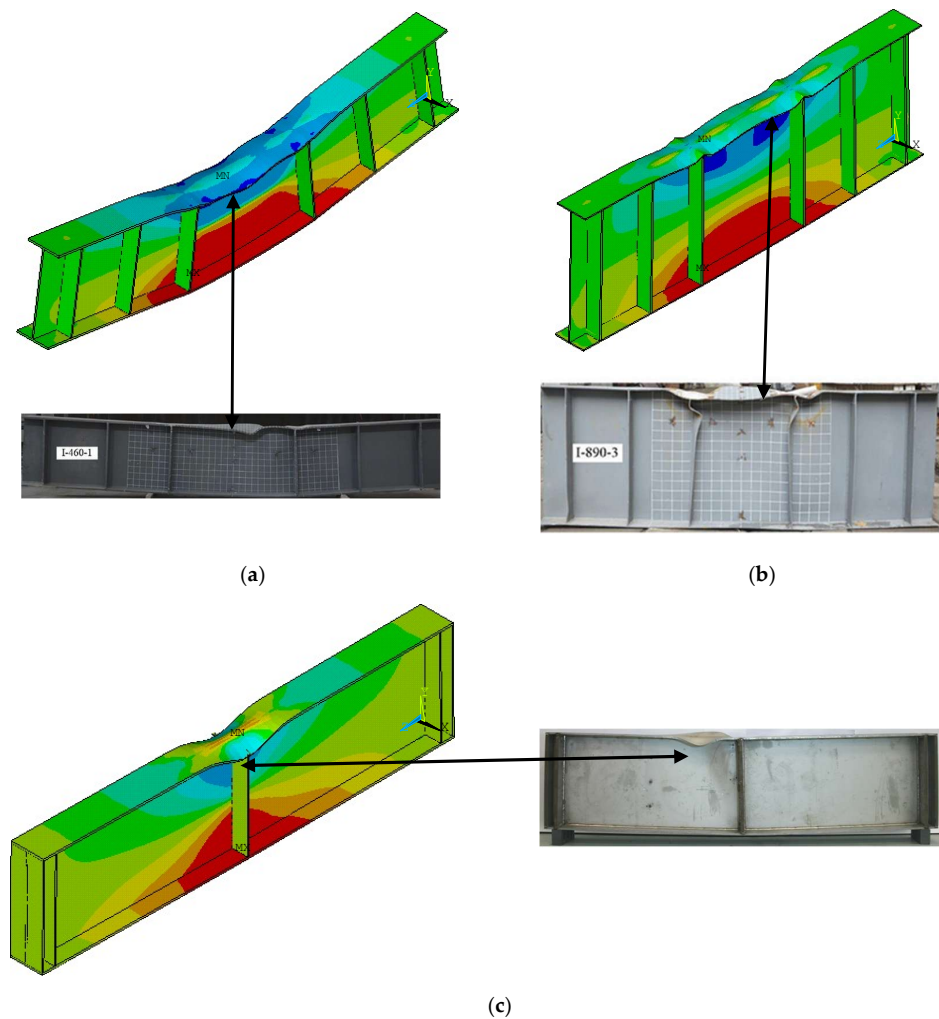


Figure 5. The deformations and buckling failure locations were obtained by FEM analysis and experimental tests. (a) I-460-1 Shi et al. [55]. (b) I-890-3 Shi et al. [55]. (c) I-600 × 200 × 12 × 10-2 Saliba and Gardner [58].

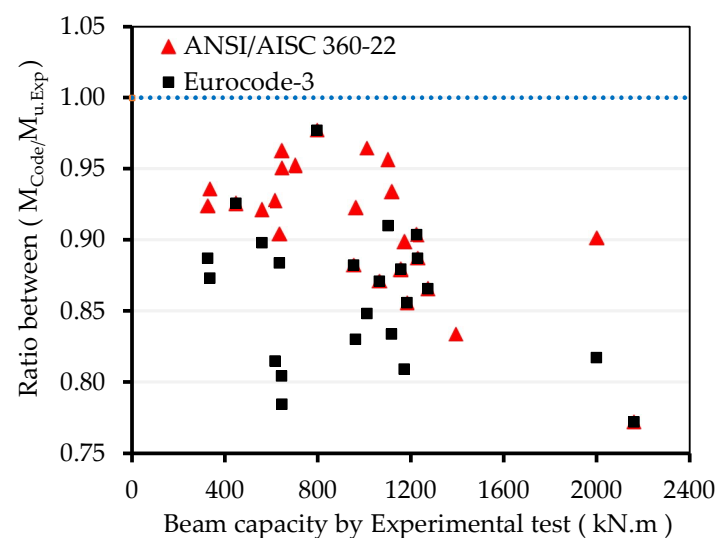


Figure 6. The ratio of bending moment resulting from both existing design codes and experimental tests.

5. Results and Discussion

To find out the effect of the presence of out-of-plane distance in the lateral direction of the length of the steel beam on its efficiency, a second group containing 116 specimens was proposed and analyzed using FEM analysis. This group included several variables related to cross-section size, steel beam length, and yield stress. All of these variables were used at different out-of-plane distances. The effect of all these variables on the behavior of the steel beam, stress distribution in the cross-section, and BFIB steel beam capacity was obtained.

5.1. Bending Moment and Deflection Relationship

The relationship between bending moment and the corresponding mid-span deflection can directly explain the behavior of steel beams. By analyzing the results of the specimens, it became clear that when there was any out-of-plane distance in the middle of the beam span, a significant decrease occurred in the steel beam capacity, at different rates depending on the value of the out-of-plane distance and the steel beam cross-section dimensions. For example, when using an out-of-plane distance of 300 mm in steel beams with BFIB-600 and BFIB-300 sections, where this distance represents the value of the beam flange width, there was a decrease in the beam capacity, which reached, respectively, 50% and 60% of the beam capacity without an out-of-plane distance. It was also observed that at this out-of-plane value, the deflection value increased when compared to the beam without an out-of-plane distance, as shown in Figure 7. With the increase in the out-of-plane distance to 2000 mm for the same beams, the reduction in the ultimate bending moment capacity reached 6% and 11%, respectively. It was also observed that the behavior of the steel beam changed from the first level of load application to the steel beam.

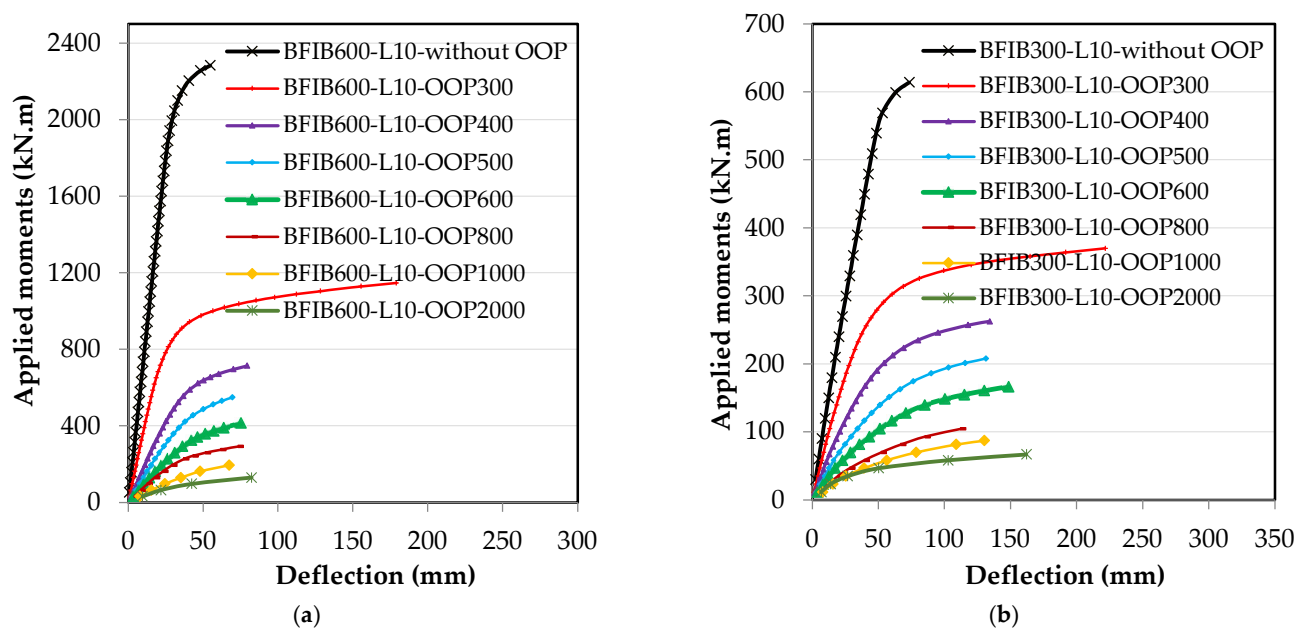


Figure 7. Bending moment and the corresponding deflection relationships obtained from FEM simulation with different out-of-plane distances. (a) BFIB-600-L10-fy282 MPa. (b) BFIB-300-L10-fy282 MPa.

5.2. Shape of Deformations and Stress Distribution

By FEM analysis of BFIB steel beams with or without an out-of-plane distance, the deformations and stress distributions of each specimen were obtained. It was observed that steel beams without out-of-plane distance failed due to local buckling at the top flange of the beam cross-section. When there is an out-of-plane distance, stresses are concentrated

in the upper flange. These stresses are the result of global buckling along the entire beam length of the upper flange, starting from the support point to the middle beam length. These stresses are in the form of compressive stresses at the inner edge of the upper flange, and they are met by tensile stresses in the same flange, but on the outer edge. The location of the concentration of these stresses is at the point of contact of the upper flange of the out-of-plane length with the upper flange of the main beam, as shown in Figure 8. Stress concentration, whether compressive or tensile, continues with the increase in the out-of-plane distance and is always at values greater than the yield stress of the steel used. The compressive and tensile stresses of the BFIB-500 section steel beam with an out-of-plane distance of 300 mm were 410 MPa, and 311 MPa, respectively, while the yield stress used was 282 MPa. These stresses appeared despite the clear reduction in the beam capacity to 55% of the beam capacity without an out-of-plane distance. With the out-of-plane distance increasing to 1000 mm, these stresses reached 306 MPa, and 352 MPa, respectively, which was also higher than the yield stress of the steel used despite the sharp decrease in the ultimate bending moment capacity, which reached 10.0%.

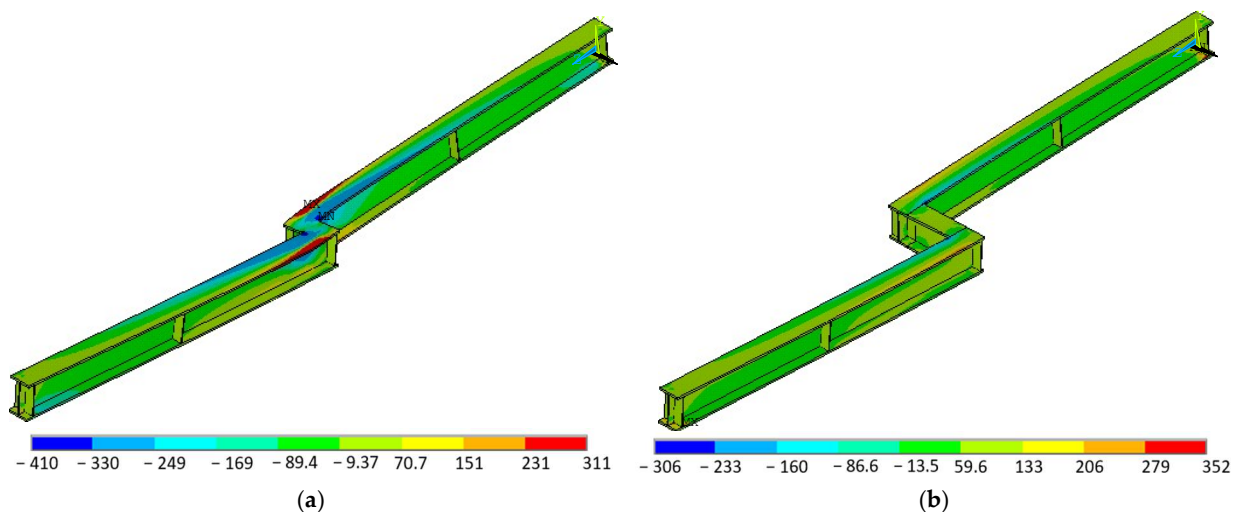


Figure 8. Deformations and stress distributions resulting from FEM simulations of the BFIB500-L10-fy282 specimen. (a) BFIB500-L10-fy282-OOP300. (b) BFIB500-L10-fy282-OOP1000.

Here, the stress distribution shape through the cross-section of the steel beam with an out-of-plane distance is accurately analyzed. The stress distribution shape through the cross-section of the longitudinal part of the steel beam was measured at the stress concentration point where the out-of-plane part contacts the longitudinal axis of the beam. The stress distribution through the cross-section was measured at different ratios of 3, 15, 25, 50, 75, and 100% of the applied load value, as shown in Figure 9. From Figure 9, it is clear that the cross-section is exposed to an irregular stress distribution on both the upper and lower flange, and this appears from the first application of the load. These stresses on a single flange, whether upper or lower, are exposed to two types of stresses, tensile stresses at the outer edge of the beam axis and compressive stresses at the inner edge, while this distribution is reflected on the lower flange, where the tensile stresses are on the inner edge and the compressive stresses are on the outer edge of the beam axis. This is evidence that the effect of the out-of-plane distance on the structural system of the steel beam causes a global buckling from the first application of the load, as shown in Figure 9a. Through this distribution of stress, it can be said that the effect of buckling on steel beams with an out-of-plane distance begins from the first moment of applying the load, which is the main factor in causing the failure of this structural system. It accelerates the increase in stress values at the stress concentration point to values exceeding the yield stress of the steel used.

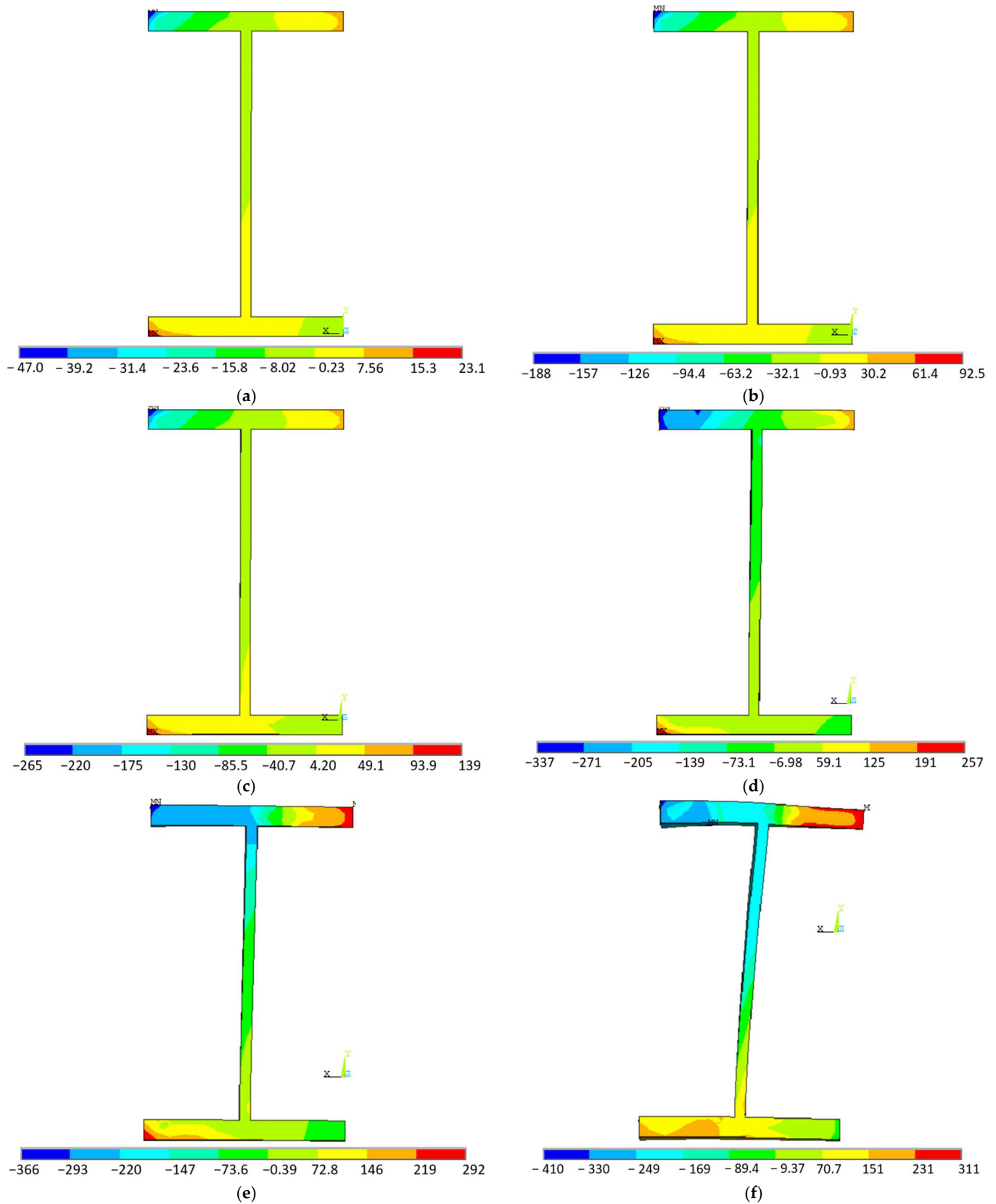


Figure 9. Stress distributions through the cross-section at the critical location of stress concentration at different applied load ratios for the BFIB500-L10-fy282-OOP300 specimen. (a) At 3% of the applied load. (b) At 15% of the applied load. (c) At 25% of the applied load. (d) At 50% of the applied load. (e) At 75% of the applied load. (f) At 100% of the applied load.

5.3. Effect of Variables and Out-of-Plane Distance on Beam Efficiency

To obtain the effect of different variables such as cross-section size, steel beam length, yield stress, and the out-of-plane distance on the efficiency of the BFIB steel beams, Figures 10–15, were constructed; these figures represent the relationship between the steel beam capacity with out-of-plane distance and the beam without out-of-plane distance for each variable separately.

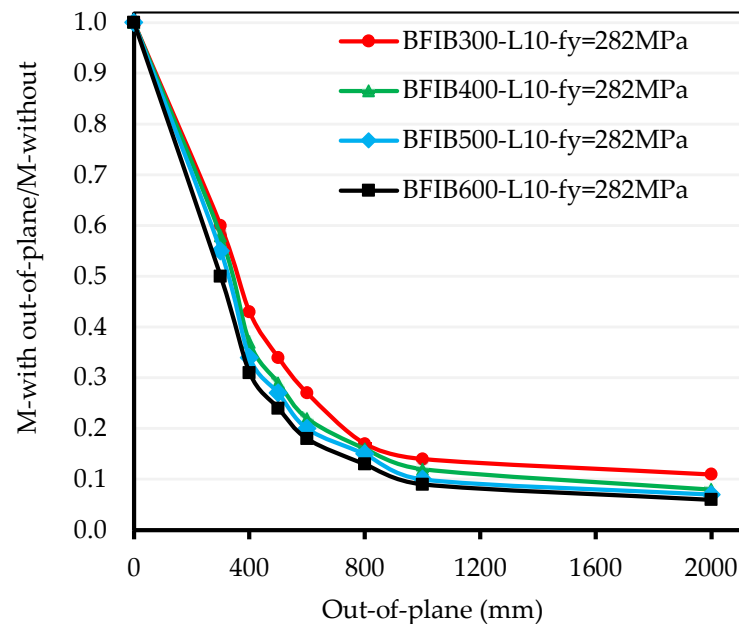


Figure 10. Relationship between moment capacity ratio and out-of-plane value for beam cross-section effect.

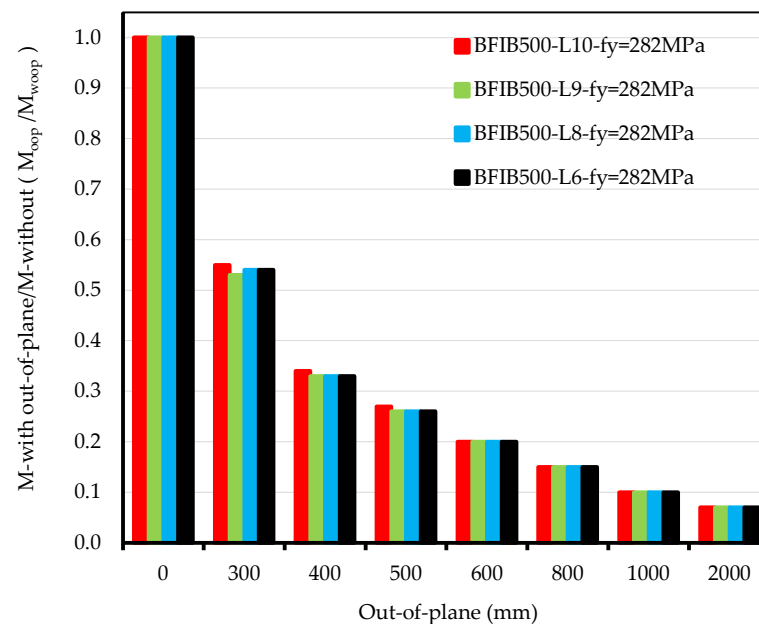


Figure 11. Relationship between moment capacity ratio and out-of-plane value for beam length effect with BFIB-500 section.

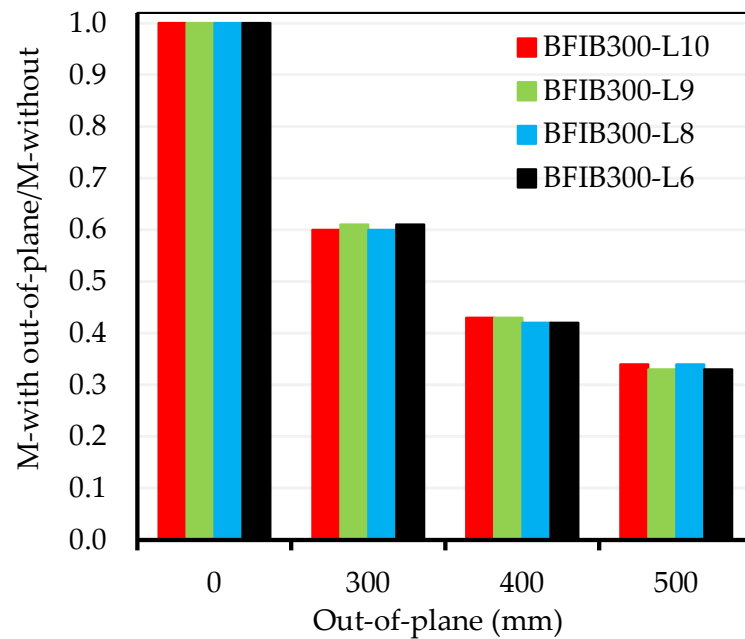


Figure 12. Relationship between moment capacity ratio and out-of-plane value for beam length effect with BFIB-300 section.

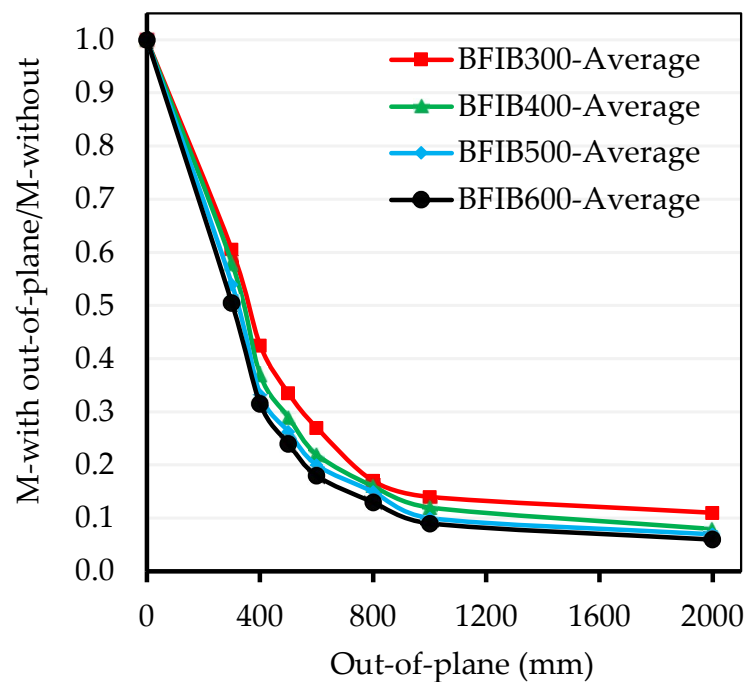


Figure 13. Relationship between average moment capacity ratios and out-of-plane value for beam length and cross-section effects.

5.3.1. Effect of Beam Cross-Sectional Dimensions

One of the most important elements that directly affect the efficiency of the steel element is the dimensions of the cross-section, as it is the basic element used in determining the ultimate capacity of bending moments, as well as in choosing the type of design category for the cross-section in terms of the compact, noncompact, and slender categories. Figure 10 shows the relationship between the effect of cross-sectional dimensions on the percentage reduction in beam capacity due to the presence of an out-of-plane distance. Different cross-sections were used to study this variable, namely BFIB-300, BFIB-400, BFIB-500, and BFIB-600, with the same out-of-plane distances. Figure 10 shows that the effect

of cross-sectional dimensions is directly proportional to the percentage reduction in beam capacity. By fixing the length of the steel beam as well as the yield stress of the steel used and using an out-of-plane distance of 300 mm with steel beams with the cross-sections BFIB-300, BFIB-400, BFIB-500 and BFIB-600, the ratio of the beam capacity with out-of-plane distance to those without it (M_{OOP}/M_{woop}) decreased by ratios equal to 0.60, 0.58, 0.55, and 0.50, respectively. With the change in the out-of-plane distance to 1000 mm, the decrease ratios of M_{OOP}/M_{woop} reached 0.14, 0.12, 0.10, and 0.09, respectively. But after the out-of-plane distance reached 1000 mm, the decrease ratio was small compared to the beginning; when the out-of-plane distance was increased to 2000 mm, the decrease ratios of M_{OOP}/M_{woop} reached 0.11, 0.08, 0.07, and 0.06, respectively. Through this, as the cross-sectional dimensions of the BFIB steel beam increase, the reduction ratio in the steel beam capacity with out-of-plane distance increases.

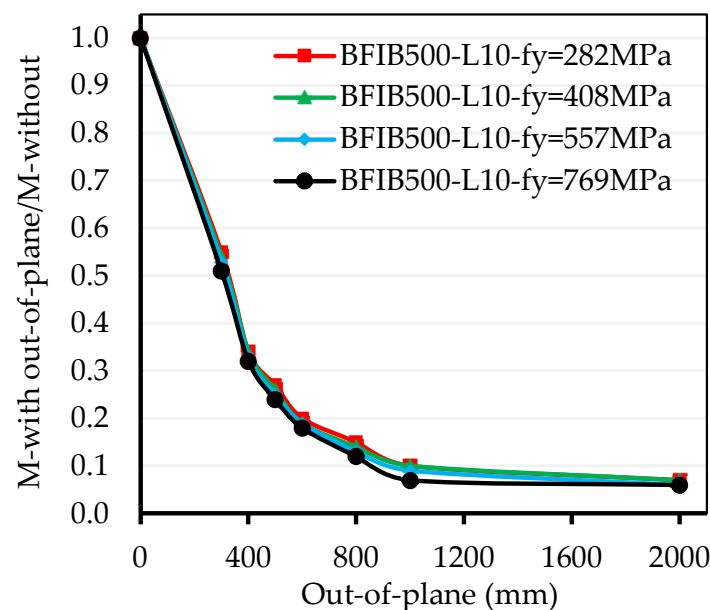


Figure 14. The relationship between average moment capacity ratios and out-of-plane value for steel beam yield stress effect.

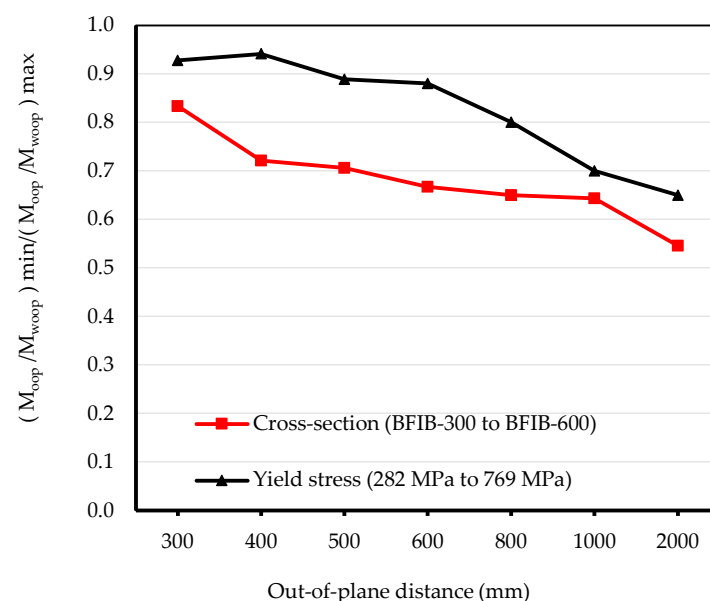


Figure 15. Minimum-to-maximum reduction ratio and out-of-plane distance relationship.

5.3.2. Effect of Beam Length

Since the length of the steel beam is the variable that causes the presence of an out-of-plane distance, it was necessary to use it as a variable to know the extent of its effect on the efficiency of the steel beams with the presence of out-of-plane distances. To verify this, steel beams of variable lengths of 6000, 8000, 9000, and 10,000 mm were used with the same section of the BFIB-500 beam and the same yield stress as the steel used. The relationship between the percentages of decrease in the ultimate capacity of bending moments with the effect of out-of-plane distances was determined, as shown in Figure 11. From Figure 11, it is clear that this variable does not affect the efficiency of the steel beam or the value of the decrease in the ultimate capacity of the bending moments with the presence of out-of-plane distance. When using an out-of-plane distance of 300 mm for steel beams of lengths 6000, 8000, 9000, and 10,000 mm, the reduction ratio of M_{OOP}/M_{woop} was 0.55, 0.53, 0.54, and 0.54, respectively. When the out-of-plane distance was increased to 2000 mm, the reduction ratio for all the lengths was 0.07.

To verify this result, the same specified lengths were used with the other cross-sections, BFIB-300, BFIB-400, and BFIB-600, and the same result was obtained, as shown in Figure 12 for cross-section BFIB-300. When using an out-of-plane distance of 300 mm for steel beams of lengths 6000, 8000, 9000, and 10000 mm, the reduction ratios of M_{OOP}/M_{woop} were 0.60, 0.61, 0.60, and 0.61, respectively. This was also measured at all out-of-plane distances used with this variable. Therefore, the two variables were combined, where the cross-sectional dimensions (which have a direct proportional effect on the percentages of decrease in the ultimate capacity) with the length of the steel beam (which has no effect) and the average of the percentages of these two variables were taken, as shown in Figure 13. It is clear from Figure 13 that it is identical to Figure 12, as the main variable for these two figures is only the dimensions of the cross-section, and there is no effect of the length of the steel beam.

5.3.3. Steel Yield Stress Effect

The yield stress of the steel used is one of the most important variables that directly affect the efficiency of steel elements as well as their ultimate capacity. Therefore, different values of this variable were used, such as 282, 408, 557, and 769 MPa, for the same beam cross-section and length, and the extent of its effect on the percentage of decrease in the ultimate capacity of bending moments with an out-of-plane distance was determined, as shown in Figure 14. As can be seen in the figure, the effect of changing the yield stress on the ultimate capacity was measured by changing the out-of-plane distance. By using an out-of-plane distance of 300 mm for steel beams with yield stresses 282, 408, 557, and 769 MPa, the decrease ratios of M_{OOP}/M_{woop} reached 0.55, 0.54, 0.53, and 0.51, respectively. The maximum value of the decrease with the variable yield stress was reached at an out-of-plane distance of 2000 mm, and the decrease value was 0.07 with yield stresses of 282 and 408 MPa, while the decrease ratio was 0.06 with yield stresses of 557 and 769 MPa.

5.3.4. Effect of Out-of-Plane Distance on Range and Rate of Change for All Variables

The previous results show the extent of the effect of an out-of-plane distance on the variables affecting the ultimate capacity, such as the dimensions of the cross-section and the yield stress of the steel used. For this purpose, the ratio between the highest rate of reduction in the M_{OOP}/M_{woop} to the lowest rate of reduction for the same variable is obtained. When using the BFIB-300 beam cross-section dimension, the reduction rates were higher than when using the BFIB-600 with all the out-of-plane distances used. Therefore, the ratio of the M_{OOP}/M_{woop} for BFIB-300 to BFIB-600 is used to obtain the relationship between the effects of the out-of-plane distances on the cross-section dimensions. Also, the decreasing rate ratio was found for steel yield stress from 282 MPa to 769 MPa, as

shown in Figure 15. From Figure 15, the rates of change due to the effect of the cross-section dimension and steel yield stress are 16.7%, and 7.3%, respectively, for out-of-plane distances of 300 mm, while the rates of change are 45.5%, and 35.0%, respectively, for out-of-plane distances of 2000 mm. From these values, the effect of the out-of-plane distances is higher for the dimensions of the cross-section than the effect of the yield stress of the steel used.

5.4. The Discussion

When steel beams with an out-of-plane distance are used, the relationship between the bending moments and the corresponding deflection increases significantly. The ultimate bending moment capacity decreases with increasing out-of-plane distance, although the corresponding deflection values increase. This is due to the loss of this type of out-of-plane steel beams to the arch system in resisting deflection, as shown in Figure 7. With the presence of an out-of-plane distance, stresses are concentrated at the outer edges of the upper flange. These stresses are of different types: one type is tensile stress at the outer edge of the beam, while the other type is compressive stress at the inner edge of the beam. These stresses result from the occurrence of a global buckling along the entire length of the steel beam in the upper flange. This dent causes an acceleration in the failure process of the beam and its inability to resist external loads. It is the main reason for the failure of this system, as it causes a large increase in stress values exceeding the yield stresses of the steel used under the influence of small load values, as shown in Figures 8 and 9.

The effect of the cross-sectional dimensions on steel beams with an out-of-plane distance is a direct effect; as the cross-sectional dimensions increase, the percentage of reduction in the ultimate capacity of the bending moments increases. This increase in the reduction is due to the approach of the cross-sectional dimensions, especially the web, to another design classification according to the design codes. The web category classification ratios approach the end of the compact category and the beginning of the noncompact category. In addition, with the increase in the web beam height, the possibility of the buckling of the upper flange increases, and this is enhanced by the presence of the concentration of two different types of stresses at the upper flange edges. As for the effect of the length of the beam, no effect was observed on the percentage of decrease in the ultimate capacity of bending moments when using an out-of-plane distance. This is because the buckling occurring at the upper flange occurs along the entire length of the beam, in addition to the fact that the critical location in which stresses are concentrated is precisely defined, where part of an out-of-plane distance connects with the longitudinal beam. The effect of the yield stresses of the steel used on the percentage of reduction in the ultimate capacity of the bending moments of steel beams with out-of-plane distance is directly proportional. As the yield stress increases, the percentage of reduction in the ultimate capacity increases. This is because, with the increase in yield stress values, the design category of the beam cross-sections changes according to the design codes. Through Equations (1) to (17), it was found that the yield stress was inversely proportional to the change in the limits of the design categories of the cross-sections. Thus, with the increase in the yield stress values, they approach the end of the compact category and the beginning of the noncompact category. This result is consistent with previous studies, such as those of Sayed and Al-Jarbou [29].

6. Prediction of Beam Capacity with Out-of-Plane Distance

The second group was used in the FEM analysis process; it contained 116 specimens of steel beams, divided into 19 specimens without an out-of-plane distance and 97 specimens with an out-of-plane distance. Different variables were used, including four types of different cross-sections, BFIB-300, BFIB-400, BFIB-500, and BFIB-600; the lengths of the

steel beams changed from 6000 mm to 10,000 mm, and different types of yield stresses were also used for the steel used, where it changes from 282 MPa to 769 MPa, as listed in Table 6. In addition, the values calculated from the current design codes, ANSI/AISC 360-22 [51] and European-3 [52], are also listed in Table 6.

Table 6. Summary of FEM results for steel I-beams with and without out-of-plane distance.

FEM Specimens	OOP (mm)	Shear Span (m)	FEM Results		ANSI/AISC 360-22 [51] Eurocode-3 [52]	
			M_{FEM} (kN.m)	M_{OOP}/M_{woop}	M_{Code} (kN.m)	M_{Code}/M_{FEM}
BFIB500-L10-fy282-without OOP	0	5.0	1648.57	1.00	1442.40	0.87
BFIB500-L10-fy282-OOP300	300	5.0	905.30	0.55	---	1.59
BFIB500-L10-fy282-OOP400	400	5.0	561.24	0.34	---	2.57
BFIB500-L10-fy282-OOP500	500	5.0	437.09	0.27	---	3.30
BFIB500-L10-fy282-OOP600	600	5.0	337.79	0.20	---	4.27
BFIB500-L10-fy282-OOP800	800	5.0	247.05	0.15	---	5.84
BFIB500-L10-fy282-OOP1000	1000	5.0	169.49	0.10	---	8.51
BFIB500-L10-fy282-OOP2000	2000	5.0	117.27	0.07	---	12.30
BFIB500-L9-fy282-without OOP	0	4.5	1700.46	1.00	1442.40	0.85
BFIB500-L9-fy282-OOP300	300	4.5	902.65	0.53	---	1.60
BFIB500-L9-fy282-OOP400	400	4.5	563.22	0.33	---	2.56
BFIB500-L9-fy282-OOP500	500	4.5	435.76	0.26	---	3.31
BFIB500-L9-fy282-OOP600	600	4.5	336.89	0.20	---	4.28
BFIB500-L9-fy282-OOP800	800	4.5	249.01	0.15	---	5.79
BFIB500-L9-fy282-OOP1000	1000	4.5	169.70	0.10	---	8.50
BFIB500-L9-fy282-OOP2000	2000	4.5	117.18	0.07	---	12.31
BFIB500-L8-fy282-without OOP	0	4.0	1695.00	1.00	1442.40	0.85
BFIB500-L8-fy282-OOP300	300	4.0	914.66	0.54	---	1.58
BFIB500-L8-fy282-OOP400	400	4.0	558.53	0.33	---	2.58
BFIB500-L8-fy282-OOP500	500	4.0	439.43	0.26	---	3.28
BFIB500-L8-fy282-OOP600	600	4.0	335.27	0.20	---	4.30
BFIB500-L8-fy282-OOP800	800	4.0	247.38	0.15	---	5.83
BFIB500-L8-fy282-OOP1000	1000	4.0	168.90	0.10	---	8.54
BFIB500-L8-fy282-OOP2000	2000	4.0	117.18	0.07	---	12.31
BFIB500-L6-fy282-without OOP	0	3.0	1691.78	1.00	1442.40	0.85
BFIB500-L6-fy282-OOP300	300	3.0	918.72	0.54	---	1.57
BFIB500-L6-fy282-OOP400	400	3.0	564.39	0.33	---	2.56
BFIB500-L6-fy282-OOP500	500	3.0	439.43	0.26	---	3.28
BFIB500-L6-fy282-OOP600	600	3.0	336.28	0.20	---	4.29
BFIB500-L6-fy282-OOP800	800	3.0	248.69	0.15	---	5.80
BFIB500-L6-fy282-OOP1000	1000	3.0	169.10	0.10	---	8.53
BFIB500-L6-fy282-OOP2000	2000	3.0	117.18	0.07	---	12.31
BFIB300-L10-fy282-without OOP	0	5.0	614.00	1.00	541.23	0.88
BFIB300-L10-fy282-OOP300	300	5.0	369.82	0.60	---	1.46
BFIB300-L10-fy282-OOP400	400	5.0	262.61	0.43	---	2.06
BFIB300-L10-fy282-OOP500	500	5.0	207.80	0.34	---	2.60
BFIB300-L10-fy282-OOP600	600	5.0	166.38	0.27	---	3.25
BFIB300-L10-fy282-OOP800	800	5.0	104.63	0.17	---	5.17
BFIB300-L10-fy282-OOP1000	1000	5.0	87.19	0.14	---	6.21
BFIB300-L10-fy282-OOP2000	2000	5.0	66.84	0.11	---	8.10
BFIB300-L9-fy282-without OOP	0	4.5	620.81	1.00	541.23	0.87
BFIB300-L9-fy282-OOP300	300	4.5	379.92	0.61	---	1.42
BFIB300-L9-fy282-OOP400	400	4.5	264.64	0.43	---	2.05
BFIB300-L9-fy282-OOP500	500	4.5	207.94	0.33	---	2.60
BFIB300-L8-fy282-without OOP	0	4.0	623.80	1.00	541.23	0.87
BFIB300-L8-fy282-OOP300	300	4.0	375.85	0.60	---	1.44
BFIB300-L8-fy282-OOP400	400	4.0	263.73	0.42	---	2.05
BFIB300-L8-fy282-OOP500	500	4.0	209.25	0.34	---	2.59

Table 6. Cont.

FEM Specimens	OOP (mm)	Shear Span (m)	FEM Results		ANSI/AISC 360-22 [51] Eurocode-3 [52]	
			M_{FEM} (kN.m)	M_{OOP}/M_{woop}	M_{Code} (kN.m)	M_{Code}/M_{FEM}
BFIB300-L6-fy282-without OOP	0	3.0	629.72	1.00	541.23	0.86
BFIB300-L6-fy282-OOP300	300	3.0	381.45	0.61	---	1.42
BFIB300-L6-fy282-OOP400	400	3.0	264.85	0.42	---	2.04
BFIB300-L6-fy282-OOP500	500	3.0	209.25	0.33	---	2.59
BFIB400-L10-fy282-without OOP	0	5.0	1109.65	1.00	960.99	0.87
BFIB400-L10-fy282-OOP300	300	5.0	640.83	0.58	---	1.50
BFIB400-L10-fy282-OOP400	400	5.0	410.68	0.37	---	2.34
BFIB400-L10-fy282-OOP500	500	5.0	317.75	0.29	---	3.02
BFIB400-L10-fy282-OOP600	600	5.0	246.06	0.22	---	3.91
BFIB400-L10-fy282-OOP800	800	5.0	178.25	0.16	---	5.39
BFIB400-L10-fy282-OOP1000	1000	5.0	129.51	0.12	---	7.42
BFIB400-L10-fy282-OOP2000	2000	5.0	93.00	0.08	---	10.33
BFIB400-L9-fy282-without OOP	0	4.5	1093.16	1.00	960.99	0.88
BFIB400-L9-fy282-OOP300	300	4.5	638.65	0.58	---	1.50
BFIB400-L9-fy282-OOP400	400	4.5	411.94	0.38	---	2.33
BFIB400-L9-fy282-OOP500	500	4.5	320.85	0.29	---	3.00
BFIB400-L8-fy282-without OOP	0	4.0	1097.59	1.00	960.99	0.88
BFIB400-L8-fy282-OOP300	300	4.0	641.31	0.58	---	1.50
BFIB400-L8-fy282-OOP400	400	4.0	407.20	0.37	---	2.36
BFIB400-L8-fy282-OOP500	500	4.0	322.40	0.29	---	2.98
BFIB400-L6-fy282-without OOP	0	3.0	1120.15	1.00	960.99	0.86
BFIB400-L6-fy282-OOP300	300	3.0	645.91	0.58	---	1.49
BFIB400-L6-fy282-OOP400	400	3.0	408.59	0.36	---	2.35
BFIB400-L6-fy282-OOP500	500	3.0	320.85	0.29	---	3.00
BFIB600-L10-fy282-without OOP	0	5.0	2283.04	1.00	1926.68	0.84
BFIB600-L10-fy282-OOP300	300	5.0	1147.39	0.50	---	1.68
BFIB600-L10-fy282-OOP400	400	5.0	714.58	0.31	---	2.70
BFIB600-L10-fy282-OOP500	500	5.0	549.28	0.24	---	3.51
BFIB600-L10-fy282-OOP600	600	5.0	415.01	0.18	---	4.64
BFIB600-L10-fy282-OOP800	800	5.0	292.95	0.13	---	6.58
BFIB600-L10-fy282-OOP1000	1000	5.0	195.30	0.09	---	9.87
BFIB600-L10-fy282-OOP2000	2000	5.0	130.20	0.06	---	14.80
BFIB600-L9-fy282-without OOP	0	4.5	2277.41	1.00	1926.68	0.85
BFIB600-L9-fy282-OOP300	300	4.5	1157.15	0.51	---	1.67
BFIB600-L9-fy282-OOP400	400	4.5	714.59	0.31	---	2.70
BFIB600-L9-fy282-OOP500	500	4.5	549.28	0.24	---	3.51
BFIB600-L8-fy282-without OOP	0	4.0	2276.29	1.00	1926.68	0.85
BFIB600-L8-fy282-OOP300	300	4.0	1146.23	0.50	---	1.68
BFIB600-L8-fy282-OOP400	400	4.0	718.89	0.32	---	2.68
BFIB600-L8-fy282-OOP500	500	4.0	546.84	0.24	---	3.52
BFIB600-L6-fy282-without OOP	0	3.0	2253.80	1.00	1926.68	0.85
BFIB600-L6-fy282-OOP300	300	3.0	1159.71	0.51	---	1.66
BFIB600-L6-fy282-OOP400	400	3.0	713.41	0.32	---	2.70
BFIB600-L6-fy282-OOP500	500	3.0	546.84	0.24	---	3.52
BFIB500-L10-fy408-without OOP	0	5.0	2341.41	1.00	2087.90	0.89
BFIB500-L10-fy408-OOP300	300	5.0	1267.99	0.54	---	1.65
BFIB500-L10-fy408-OOP400	400	5.0	792.44	0.34	---	2.63
BFIB500-L10-fy408-OOP500	500	5.0	616.74	0.26	---	3.39
BFIB500-L10-fy408-OOP600	600	5.0	453.87	0.19	---	4.60
BFIB500-L10-fy408-OOP800	800	5.0	327.79	0.14	---	6.37
BFIB500-L10-fy408-OOP1000	1000	5.0	222.47	0.10	---	9.39
BFIB500-L10-fy408-OOP2000	2000	5.0	156.88	0.07	---	13.31

Table 6. Cont.

FEM Specimens	OOP (mm)	Shear Span (m)	FEM Results		ANSI/AISC 360-22 [51] Eurocode-3 [52]	
			M_{FEM} (kN.m)	M_{OOP}/M_{woop}	M_{Code} (kN.m)	M_{Code}/M_{FEM}
BFIB500-L10-fy557-without OOP	0	5.0	3160.82	1.00	2848.99	0.90
BFIB500-L10-fy557-OOP300	300	5.0	1660.14	0.53	---	1.72
BFIB500-L10-fy557-OOP400	400	5.0	1046.59	0.33	---	2.72
BFIB500-L10-fy557-OOP500	500	5.0	790.21	0.25	---	3.61
BFIB500-L10-fy557-OOP600	600	5.0	588.72	0.19	---	4.84
BFIB500-L10-fy557-OOP800	800	5.0	417.23	0.13	---	6.83
BFIB500-L10-fy557-OOP1000	1000	5.0	268.67	0.09	---	10.60
BFIB500-L10-fy557-OOP2000	2000	5.0	192.71	0.06	---	14.78
BFIB500-L10-fy769-without OOP	0	5.0	4368.50	1.00	3933.35	0.90
BFIB500-L10-fy769-OOP300	300	5.0	2227.32	0.51	---	1.77
BFIB500-L10-fy769-OOP400	400	5.0	1398.09	0.32	---	2.81
BFIB500-L10-fy769-OOP500	500	5.0	1062.51	0.24	---	3.70
BFIB500-L10-fy769-OOP600	600	5.0	790.61	0.18	---	4.98
BFIB500-L10-fy769-OOP800	800	5.0	524.22	0.12	---	7.50
BFIB500-L10-fy769-OOP1000	1000	5.0	323.26	0.07	---	12.17
BFIB500-L10-fy769-OOP2000	2000	5.0	266.46	0.06	---	14.76

First stage: The simulation results of the BFIB steel beams without and with out-of-plane spacing were used to verify the accuracy of the existing codes, Eurocode-3 and ANSI/AISC 360-22. First, the FEM analysis results of the BFIB cross-section steel beams without out-of-plane distance were compared with the prediction results obtained from existing design code calculations [49,50], as shown in Figure 16. By determining the dimensions of the cross-sections and calculating the design category for each section according to the design codes, it became clear that all the specimens from the type BFIB fell into the compact category according to ANSI/AISC 360-22 and the Class-1 category according to Eurocode-3. From Figure 16, it is clear that the values of the ultimate beam moment capacity without out-of-plane distance resulting from the design codes are always less than the ultimate beam capacity resulting from the FEM simulation. This means that it falls on the safe side of the design. The average M_{Code}/M_{FEM} ratio was 0.867 with a correlation coefficient value of 0.999 and a COV of 2.072%, and this was the case for all the design codes of ANSI/AISC 360-22 and European-3. This result is in complete agreement with the conclusions available from previous studies and with Sayed and Aljarbou [29] and Pereira and Mahendran [30].

Secondly, the predicted results from the current design codes were compared with the beam capacity with out-of-plane distance, as shown in Figures 17–20. The ratio between M_{wCode}/M_{oopFEM} and the out-of-plane distance was compared for the variable cross-section dimensions, as shown in Figure 17. It is clear from Figure 17 that all the specimens with out-of-plane distance fall outside the design safe zone, where the predicted values generated by the current design codes are always larger than the actual values generated by FEM simulation. It was found that when using an out-of-plane distance of 300 mm with the cross-sections of dimensions BFIB-300, BFIB-400, BFIB-500, and BFIB-600, the ratios between the values predicted from the design codes and the values of the FEM results of M_{wCode}/M_{oopFEM} were equal to 1.46, 1.50, 1.59, and 1.68, respectively. This difference increased with the increase in the out-of-plane distance, and when this distance reached 2000 mm for the same cross-section of steel beams, the ratios between the M_{wCode}/M_{oopFEM} values were equal to 8.10, 10.33, 12.30, and 14.80, respectively. From this result, it is clear that the effect of the cross-section dimensions is directly proportional to the increase in the ratio between the prediction of the design codes and the results of the numerical analysis.

This is explained by the fact that with the increase in the dimensions of the cross-section of the beam, the height of the web increases; thus, the ratio between the height of the web and the thickness increases, which brings these ratios closer to the maximum limit of the design category according to the existing codes. Thus, the cross-sectional resistance changes as the design category of the beam approaches the end of the compact category and the beginning of the noncompact category; this causes the clear difference shown in Figure 17.

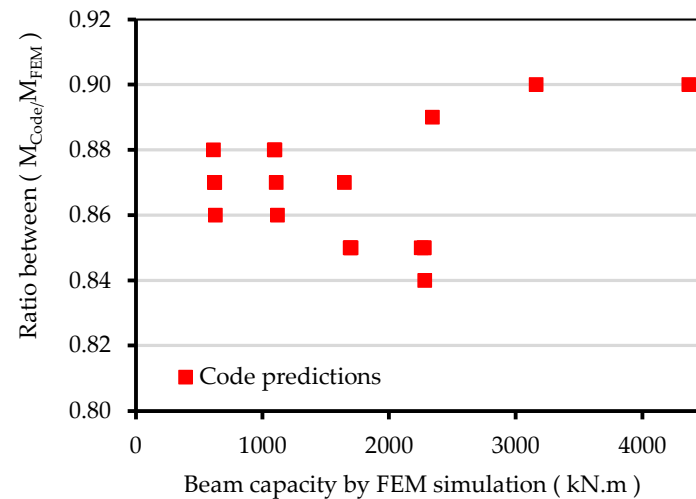


Figure 16. Bending moment ratio between current design codes [51,52] and FEM results for the beam without out-of-plane distance.

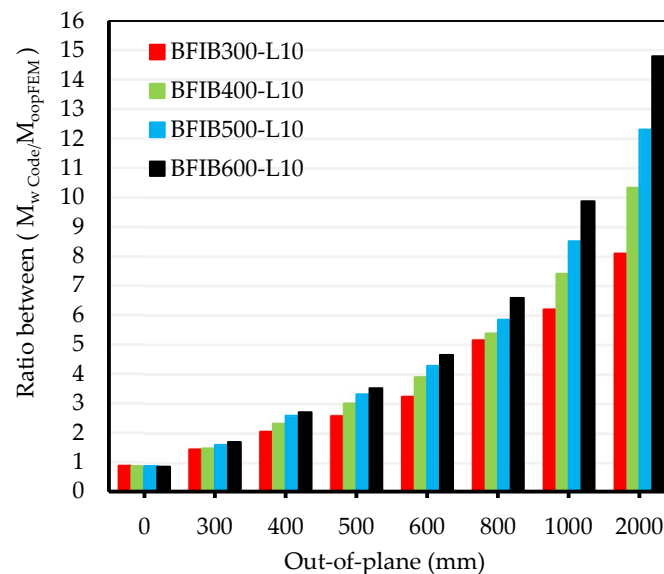


Figure 17. Comparison of existing design codes [51,52] and out-of-plane value for beam cross-section effect.

Regarding the effect of the length of the steel beam on the prediction values of the ultimate bending moment capacity for the current design codes, the relationship between the prediction ratio from the design codes and the ultimate bending moment capacity for the same steel beams with out-of-plane distances was established, as shown in Figure 18. From Figure 18 it is clear that the effect of the length of the steel beam does not affect the prediction values resulting from the current design codes. When using an out-of-plane distance of 300 mm for steel beams of lengths 6000, 8000, 9000, and 10,000 mm, the reduction ratios M_{wCode}/M_{oopFEM} were 1.59, 1.60, 1.58, and 1.57, respectively. When the out-of-plane distance was increased to 2000 mm, the reduction ratio for all the lengths was 12.31 for

all the beam lengths. This result is similar to the same result obtained previously when studying the effect of steel beam length on the reduction value of the ultimate bending moment capacity of BFIB steel beams with out-of-plane distances.

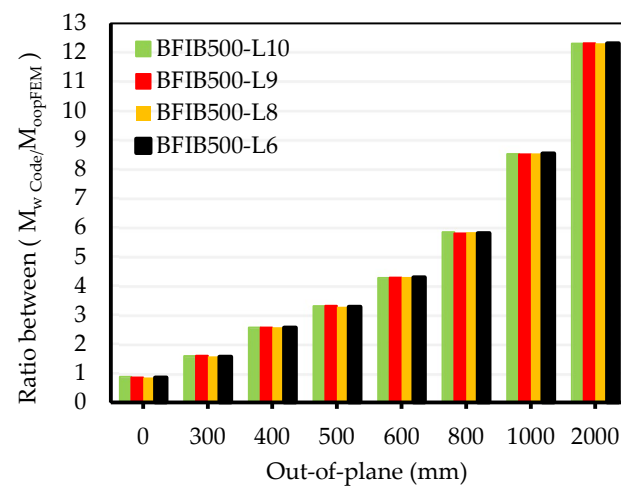


Figure 18. Comparison of existing design codes [51,52] and out-of-plane value for beam length effect with BFIB 500 section.

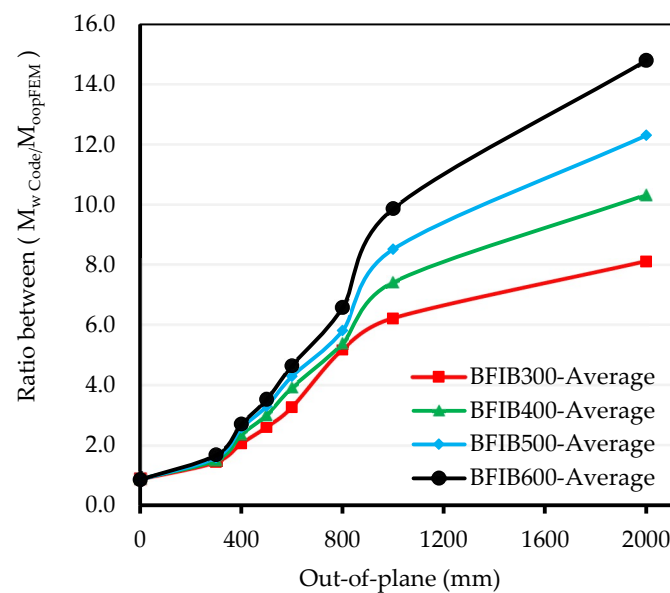


Figure 19. Comparison of average moment capacity ratios from current design codes [51,52] and out-of-plane value for beam length and cross-section effects.

Therefore, the two variables were combined, where the cross-sectional dimensions (which have a direct proportional effect on the percentages of decrease in the ultimate capacity) with the length of the steel beam (which has no effect) and the average of the percentages of these two variables were taken, as shown in Figure 13. Therefore, the average M_{wCode}/M_{oopFEM} ratio for BFIB-300 to BFIB-600 is used to obtain the relationship between the effects of the out-of-plane distances on the cross-section dimensions. From Figure 19, the range and rate of the change in the variable with out-of-plane distances of 300 mm and 2000 mm are 15.97% and 82.72%, respectively.

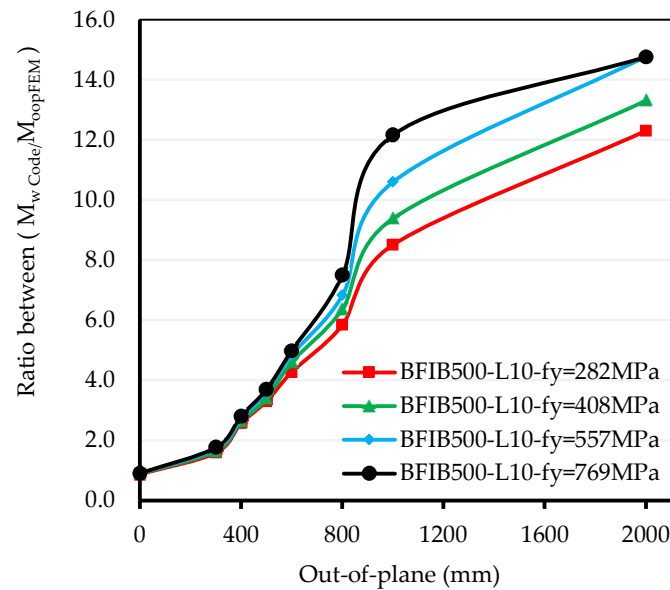


Figure 20. Comparison of average moment capacity ratios from current design codes [51,52] and out-of-plane value for steel beam yield stress effect.

The effect of changing the yield stress of the steel used on the prediction values of the existing design codes was also studied by changing the out-of-plane distance, as shown in Figure 20. By using an out-of-plane distance of 300 mm with steel beams with yield stresses of 282, 408, 557, and 769 MPa, the ratio of M_{wCode}/M_{oopFEM} reached 1.59, 1.65, 1.72, and 1.77, respectively. The maximum value of the ratio with variable yield stress was reached at an out-of-plane distance of 2000 mm, and the ratios of M_{wCode}/M_{oopFEM} reached 12.30, 13.31, 14.78, and 14.76, respectively. The ratio of M_{wCode}/M_{oopFEM} for the steel yield stresses of 282 MPa and 769 MPa was used to obtain the relationship between the effects of out-of-plane distances and predicted values from the current design codes. From Figure 20, it is clear that the prediction values from the existing design codes are directly proportional to the increase in yield stress values. This is due to the fact that yield stresses are inversely proportional to the maximum limits of the design categories (Equations (1) to (17)), which changes the resistance of the cross-sections due to their transition from one design category to another or from the increase in the ratios to the end of the current category and the beginning of a new design category. Through these proportions, the range and rate of the change in the variable with out-of-plane distances of 300 mm and 2000 mm are 11.32% and 20.00%, respectively.

Second stage: Using the above results, a new model can be obtained to predict the reduction ratio of the ultimate BFIB beam moment capacity with off-plan distance. From Table 6 and Figures 10–15, the variables have a direct relationship with the reduction ratio in the BFIB beam capacity when used as an out-of-plane value, in terms of out-of-plane distance, cross-sectional dimensions, and steel beam yield stress. As a result, factor K takes the effect of the variables, as was proposed in Equation (19). The value of the out-of-plane distance was added as a direct value to the relationship, as well as the value of the yield stress of the steel used. Since all the sections fell within the compact category according to the design codes, the cross-section dimensions were replaced by the plastic section modulus of the cross-section. The relationship between the M_{OOP}/M_{woop} ratios and the K factor was plotted, as shown in Figure 21.

$$K = OOP \times S_{Pl} \times f_y \quad (19)$$

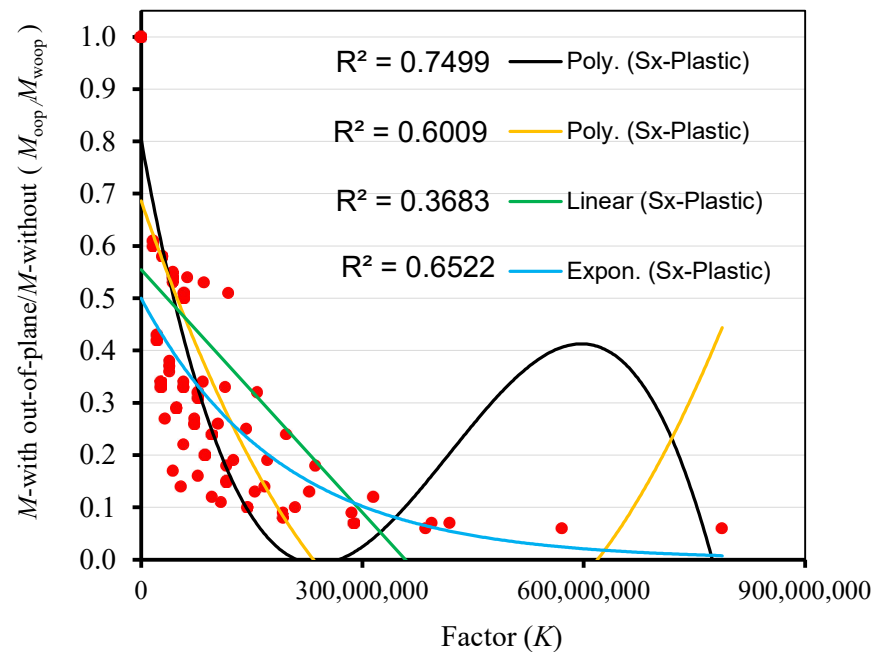


Figure 21. The relationship between moment capacity reduction ratio and factor K was obtained from FEM analysis.

Four different types of functions were used for all of these values; the functions were linear, exponential, second-degree polynomial, and third-degree polynomial. This was to obtain the best possible function that could be relied upon when proposing a model that could predict the percentage of reduction in the ultimate capacity of bending moments for steel beams with an out-of-plane distance. It is clear from Figure 21 that the linear effect of the variables does not give sufficient accuracy in predicting the ultimate BFIB steel beam capacity with the out-of-plane distance. This is evident from a coefficient of determination R^2 which comes from the third-degree polynomial relationship, in which the largest possible value is 0.7499. In order to obtain higher accuracy in the results, it was necessary to change the effect of the variables from linear to nonlinear, through trial and error. The power of the variables was changed, and the coefficient of determination was measured each time to reach the best possible value. From this result, a modification of the K_m factor was obtained, and it became that used in Equation (20). After applying the factor K_m , the calculated values were very large numbers, as the variables were placed in the equation in millimeters; so, the number 10,000 was used to achieve mathematically accepted values.

$$K_m = OOP \times S_{pl}^{0.18} \times f_y^{0.10} / 10000 \quad (20)$$

The relationship between the M_{oop}/M_{woop} ratio and the new factor K_m was plotted, as shown in Figure 22. Through the third-degree polynomial function, which has the highest coefficient of determination value, Equation (21) was obtained with a coefficient of determination equal to 0.9907. The new models can predict the ultimate BFIB steel beam capacity with out-of-plane distance as a ratio of the ultimate capacity of steel beams without out-of-plane distance with high accuracy and a coefficient of correlation of 0.995. From Figure 22 and the third-order polynomial function used to propose the new model, it is clear that increasing the value of the factor K_m above 6.0 gives incorrect prediction values for the reduction ratios of the steel beams with an out-of-plane distance. Therefore, a limit of this factor K_m was set which should not exceed 6.0 when applying Equation (21) to predict the reduction ratios of these steel beams.

$$\frac{M_{oop}}{M_{woop}} = -0.0168K_m^3 + 0.2009K_m^2 - 0.7592K_m + 1.0048 \quad \text{where } K_m \leq 6.0 \quad (21)$$

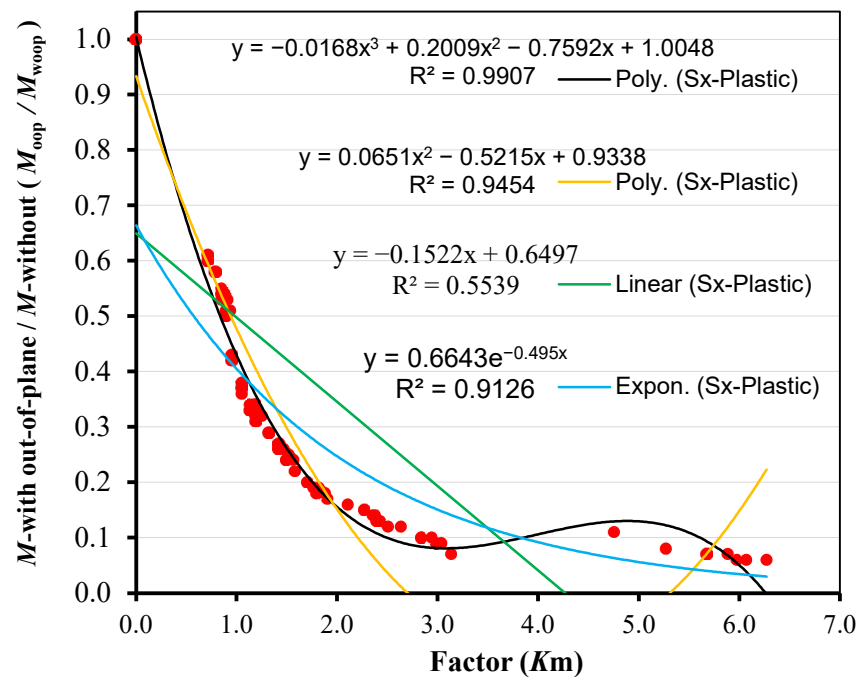


Figure 22. Relationship between moment capacity reduction ratio and the modification factor K_m .

7. Conclusions

The possibility of an out-of-plane distance for steel beams in the lateral direction along their length can occur as a result of deviations in the edges of the area to be covered or the presence of obstacles in the natural direction along the length of the beam. To study this research point, firstly, the FEM simulation results were verified by comparing them with the beams available in previous studies without out-of-plane distance in their length. The results were accurate with an average beam capacity ratio of 1.007, a coefficient of correlation of 0.999, and a COV of 1.573%. Secondly, FEM modeling was performed on BFIB steel beams with and without out-of-plane distance to take into account different variables, such as out-of-plane distance, cross-section dimensions, length of steel beams, and yield stress of steel beams. Through this study, the following conclusions were reached:

- The existing design codes were used to predict the BFIB beam capacity without out-of-plane distance in the compact category; both the FEM simulation results and the experimental test results were less than the steel beam capacity.
- The existing design codes were used to predict the beam capacity, and any application of the out-of-plane distance was more than the steel beam capacity, i.e., they were on the unsafe side of the design.
- The reduction ratios of the ultimate moment capacity in out-of-plane BFIB steel beams were directly proportional to the out-of-plane distance, cross-sectional dimensions, and yield stress of the steel beams, while the length of the steel beams had no effect.
- The effect of cross-sectional dimensions and steel yield stress on the reduction ratios was nonlinear, except for the out-of-plane distance which was linear.
- When an out-of-plane distance of 300 mm was applied to the BFIB-300 steel beam, this distance was only equal to the width of the cross-section flange of the steel beam; the reduction ratio in the ultimate moment capacity was 0.60. As the cross-sectional dimensions increased, the reduction ratio increased, reaching 0.50 with the BFIB-600 steel beam.

- In steel beams that contain an out-of-plane distance, failure is always due to the concentration of compressive stresses at the inner edge; there is a concentration of tensile stresses at the outer edge of the upper flange at the point of contact with the out-of-plane distance that results from global buckling along the entire length of the beam.

This study resulted in several research points that can be used in future studies. Conducting experimental tests on these steel beams with an out-of-plane distance included the use of several variables that were proven to affect the efficiency of these structural elements. Studying these steel beams with an out-of-plane distance using different support ends, such as their connection to steel columns, caused a difference in the structural system and thus a difference in the results. Various other locations along the beam axis where there is an out-of-plane distance need to be considered, such as one-quarter and one-third of the beam length. Other cross-sections used in the manufacture of steel beams, whether hot-formed or built-up sections, can also be studied.

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

Funding: This research received no external funding.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The author extends the appreciation to the Deanship of Postgraduate Studies and Scientific Research at Majmaah University for funding this research work through the project number (R-2025-1531).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lee, C.H.; Han, K.H.; Uang, C.M.; Kim, D.-K.; Park, C.-H.; Kim, J.-H. Flexural strength and rotation capacity of I-shaped beams fabricated from 800 MPa steel. *J. Struct. Eng.* **2013**, *139*, 1043–1058. [\[CrossRef\]](#)
2. Thomas, S.J.; Earls, C.J. Cross-sectional compactness and bracing requirements for HPS483W girders. *J. Struct. Eng.* **2003**, *129*, 1569–1583. [\[CrossRef\]](#)
3. Han, Y.; Li, N.; Zhang, G. Study on flexural behavior of corroded i-shaped steel beams strengthened with hybrid CFRP/GFRP sheets. *Materials* **2023**, *16*, 5080. [\[CrossRef\]](#)
4. Earls, C.J.; Shah, B.J. High performance steel bridge girder compactness. *J. Constr. Steel Res.* **2002**, *58*, 859–880. [\[CrossRef\]](#)
5. Green, P.S.; Sause, R.; Ricles, J.M. Strength and ductility of HPS flexural members. *J. Constr. Steel Res.* **2002**, *58*, 907–941. [\[CrossRef\]](#)
6. Earls, C.J. Uniform moment behavior of high performance steel I-shaped beams. *J. Constr. Steel Res.* **2001**, *57*, 711–728. [\[CrossRef\]](#)
7. Xue, J.; Ma, S.; Chen, X.; Wu, Q.; Wang, Y.; Wang, Y.; Akbar, M.; Yang, N. Experimental investigation and design of novel hollow flange beams under bending. *Buildings* **2024**, *14*, 1413. [\[CrossRef\]](#)
8. El-Mahdy, G.M.; El-Saadaway, M.M. Ultimate strength of singly symmetric I-section steel beams with variable flange ratio. *Thin-Walled Struct.* **2015**, *87*, 149–157. [\[CrossRef\]](#)
9. Hamoda, A.; Yehia, S.A.; Ahmed, M.; Sennah, K.; Abadel, A.A.; Shahin, R.I. Experimental and numerical investigation of shear strengthening of simply supported deep beams incorporating stainless steel plates. *Buildings* **2024**, *14*, 3680. [\[CrossRef\]](#)
10. Elamary, A.S.; Mohamed, M.A.; Sharaky, I.A.; Mohamed, A.K.; Alharthi, Y.M.; Ali, M.A.M. Utilizing artificial intelligence approaches to determine the shear strength of steel beams with flat webs. *Metals* **2023**, *13*, 232. [\[CrossRef\]](#)
11. Nikoomanesh, M.R.; Goudarzi, M.A. Experimental and numerical evaluation of shear load capacity for sinusoidal corrugated web girders. *Thin-Walled Struct.* **2020**, *153*, 106798. [\[CrossRef\]](#)

12. Jäger, B.; Kövesdi, B.; Dunai, L. Numerical investigations on bending and shear buckling interaction of I-Girders with slender WEB. *Thin-Walled Struct.* **2019**, *143*, 106199. [\[CrossRef\]](#)
13. Lim, J.; Kang, Y.-J.; Lee, J.; Kim, S.; Lee, K. Experimental and analytical study of horizontally curved i-girders subjected to equal end moments. *Metals* **2021**, *11*, 1132. [\[CrossRef\]](#)
14. Andrade, A.; Camotim, D. Lateral-torsional buckling of singly symmetric web-tapered beams: Theory and application. *J. Eng. Mech. ASCE* **2005**, *131*, 586–597. [\[CrossRef\]](#)
15. Andrade, A.; Camotim, D.; Dinis, P.B. Lateral-torsional buckling of singly symmetric web-tapered thin-walled I-beams: 1D model vs. shell FEA. *Comput. Struct.* **2007**, *85*, 1343–1359. [\[CrossRef\]](#)
16. Mascolo, I.; Modano, M.; Fiorillo, A.; Fulgione, M.; Pasquino, V.; Fraternali, F. Experimental and numerical study on the lateral-torsional buckling of steel c-beams with variable cross-section. *Metals* **2018**, *8*, 941. [\[CrossRef\]](#)
17. Asgarian, B.; Soltani, M.; Mohri, F. Lateral-torsional buckling of tapered thin-walled beams with arbitrary cross-sections. *Thin-Walled Struct.* **2013**, *62*, 96–108. [\[CrossRef\]](#)
18. Tan, L.; Zhou, Y.; Kong, H.; Yue, Z.; Wang, Q.; Zhou, L. Dynamic monitoring of steel beam stress based on PMN-PT sensor. *Buildings* **2024**, *14*, 2831. [\[CrossRef\]](#)
19. Sayed, A.M. Numerical study of the effects of flange damage on the steel beam capacity under static and fatigue flexural loads. *Results Eng.* **2023**, *17*, 100835. [\[CrossRef\]](#)
20. Nasery, M.M. Investigation on behaviours along weak axes of steel beam under low velocity impact loading: Experimental and numerical. *Buildings* **2023**, *13*, 2331. [\[CrossRef\]](#)
21. Narendra, P.V.R.; Singh, K.D. Elliptical hollow section steel cantilever beams under extremely low cycle fatigue flexural load—a finite element study. *Thin-Walled Struct.* **2017**, *119*, 126–150. [\[CrossRef\]](#)
22. Yuan, H.X.; Wang, Y.Q.; Gardner, L.; Shi, Y.J. Local-overall interactive buckling of welded stainless steel box section compression members. *Eng. Struct.* **2014**, *67*, 62–76. [\[CrossRef\]](#)
23. Cai, M.; Liu, S.; Wang, F. Temperature effect of composite girders with corrugated steel webs considering local longitudinal stiffness of webs. *Buildings* **2024**, *14*, 1939. [\[CrossRef\]](#)
24. Abed, F.; Abdul-Latif, A.; Yehia, A. Experimental study on the mechanical behavior of en08 steel at different temperatures and strain rates. *Metals* **2018**, *8*, 736. [\[CrossRef\]](#)
25. Hu, W.; Zhang, Z.; Shi, J.; Chen, Y.; Li, Y.; Feng, Q. Refined analysis of spatial three-curved steel box girder bridge and temperature stress prediction based on WOA-BPNN. *Buildings* **2024**, *14*, 415. [\[CrossRef\]](#)
26. Saliba, N.; Real, E.; Gardner, L. Shear design recommendations for stainless steel plate girders. *Eng. Struct.* **2014**, *59*, 220–228. [\[CrossRef\]](#)
27. EN 1993-1-4; Eurocode 3: Design of Steel Structures—Part 1.4: General Rules Supplementary Rules for Stainless Steel. CEN: Brussels, Belgium, 2006.
28. EN 1993-1-5; Eurocode 3: Design of Steel Structures—Part 1.5: Plated Structural Elements. CEN: Brussels, Belgium, 2006.
29. Sayed, A.M.; Aljarbou, M.H. Numerical study of the effect of circular openings in the upper surface of rectangular hollow flange steel beams on the sectional moment capacity. *Results Eng.* **2024**, *24*, 103620. [\[CrossRef\]](#)
30. Perera, N.; Mahendran, M. Section moment capacity tests of hollow flange steel plate girders. *J. Constr. Steel Res.* **2018**, *148*, 97–111. [\[CrossRef\]](#)
31. Graciano, C. Strength of longitudinally stiffened webs subjected to concentrated loading. *J. Struct. Eng.* **2005**, *131*, 268–278. [\[CrossRef\]](#)
32. Silwal, P.K.; Parvin, A.; Alhusban, M. Numerical investigation on strengthening of steel beams for corrosion damage or web openings using carbon fiber reinforced polymer sheets. *Buildings* **2024**, *14*, 1069. [\[CrossRef\]](#)
33. Zhang, X.; Yu, S.; Feng, S.; Fan, D.; Zhang, F.; Cao, H. Study on the bending performance of prefabricated h-shaped steel beams with different bolt hole types. *Buildings* **2024**, *14*, 2988. [\[CrossRef\]](#)
34. Yu, N.T.; Kim, B.; Yuan, W.B.; Li, L.Y.; Yu, F. An analytical solution of distortional buckling resistance of cold-formed steel channel-section beams with web openings. *Thin-Walled Struct.* **2019**, *135*, 446–452. [\[CrossRef\]](#)
35. El-Ariss, B.; Elkholy, S. Feasibility of reusing damaged steel beams in temporary structures. *Infrastructures* **2021**, *6*, 69. [\[CrossRef\]](#)
36. Hou, W.; Wang, L.; Shi, D. Flexural behaviour of strengthened damaged steel beams using carbon fibre-reinforced polymer sheets. *Sci. Rep.* **2022**, *12*, 10134. [\[CrossRef\]](#)
37. Kumar, S.; Gupta, P.K.; Iqbal, M.A. Experimental and numerical study on self-compacting alkali-activated slag concrete-filled steel tubes. *J. Constr. Steel Res.* **2024**, *214*, 108453. [\[CrossRef\]](#)
38. Wang, Y.-B.; Li, G.-Q.; Chen, S.-W.; Sun, F.-F. Experimental and numerical study on the behavior of axially compressed high strength steel box-columns. *Eng. Struct.* **2014**, *58*, 79–91. [\[CrossRef\]](#)
39. Rabi, M.; Ferreira, F.P.V.; Abarkan, I.; Limbachiya, V.; Shamass, R. Prediction of the cross-sectional capacity of cold-formed CHS using numerical modelling and machine learning. *Results Eng.* **2023**, *17*, 100902. [\[CrossRef\]](#)
40. Al-Kaseasbeh, Q. Analysis of hydrocarbon fire-exposed cold-formed steel columns. *Results Eng.* **2023**, *20*, 101400. [\[CrossRef\]](#)

41. Chan, C.L.; Khalid, Y.A.; Sahari, B.B.; Hamouda, A.M.S. Finite element analysis of corrugated web beams under bending. *J. Constr. Steel Res.* **2002**, *58*, 1391–1406. [[CrossRef](#)]
42. Zhang, Y.C.; Chen, Y. Experimental study and finite element analysis of square stub columns with straight ribs of concrete-filled thin-walled steel tube. *J. Build. Struct.* **2006**, *27*, 16–22.
43. Shao, Y.B.; Mohamed, H.S.; Wang, L.; Wu, C.S. Experimental and numerical investigation on stiffened rectangular hollow flange beam. *Int. J. Steel Struct.* **2020**, *20*, 1564–1581. [[CrossRef](#)]
44. Erdal, F.; Tunca, O.; Tas, S.; Ozelik, R. Experimental and finite element study of optimal designed steel corrugated web beams. *Adv. Struct. Eng.* **2021**, *24*, 1814–1827. [[CrossRef](#)]
45. Isleem, H.F.; Chukka, N.D.K.R.; Bahrami, A.; Oyeibisi, S.; Kumar, R.; Qiong, T. Nonlinear finite element and analytical modelling of reinforced concrete filled steel tube columns under axial compression loading. *Results Eng.* **2023**, *19*, 101341. [[CrossRef](#)]
46. Uzzaman, A.; Lim, J.B.P.; Nash, D.; Rhodes, J.; Young, B. Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions—Part I: Tests and finite element analysis. *Thin-Walled Struct.* **2012**, *56*, 38–48. [[CrossRef](#)]
47. Xue, J.; Ma, S.; Chen, X.; Wu, Q.; Akbar, M. Finite element modeling of assembling rivet-fastened rectangular hollow flange beams in bending. *J. Constr. Steel Res.* **2023**, *211*, 108177. [[CrossRef](#)]
48. Senapati, S.; Sangle, K.K. Nonlinear static analysis of cold-formed steel frame with rigid connections. *Results Eng.* **2022**, *15*, 100503. [[CrossRef](#)]
49. Perera, N.; Mahendran, M. Finite element analysis and design for section moment capacities of hollow flange steel plate girders. *Thin-Walled Struct.* **2019**, *135*, 356–375. [[CrossRef](#)]
50. Tao, Z.; Wang, Z.-B.; Yu, Q. Finite element modelling of concrete-filled steel stub columns under axial compression. *J. Construct. Steel Res.* **2013**, *89*, 121–131. [[CrossRef](#)]
51. ANSI/AISC 360-22; Specification for Structural Steel Buildings. American Institute of Steel Construction: Chicago, IL, USA, 2022.
52. EN 1993-1-1: 2005; Eurocode 3: Design of Steel Structures-Part 1-1: General Rules and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 2005.
53. ANSYS. *ANSYS Help User's Manual, Version 22*; Swanson Analysis Systems, Inc.: Technology Drive Canonsburg, PA, USA, 2022.
54. Sayed, A.M.; Alanazi, H. Performance of steel metal prepared using different welding cooling methods. *Case Stud. Constr. Mater.* **2022**, *16*, e00953. [[CrossRef](#)]
55. Shi, Y.; Xu, K.; Shi, G.; Li, Y. Local buckling behavior of high strength steel welded I-section flexural members under uniform moment. *Adv. Struct. Eng.* **2018**, *21*, 93–108. [[CrossRef](#)]
56. Shokouhian, M.; Shi, Y.J. Flexural strength of hybrid steel I-beams based on slenderness. *Eng. Struct.* **2015**, *93*, 114–128. [[CrossRef](#)]
57. Yang, B.; Dong, M.; Han, Q.; Elchalakani, M.; Xiong, G. Flexural behavior and rotation capacity of welded i-beams made from 690-mpa high-strength steel. *J. Struct. Eng.* **2021**, *147*, 04020320. [[CrossRef](#)]
58. Saliba, N.; Gardner, L. Experimental study of the shear response of lean duplex stainless steel plate girders. *Eng. Struct.* **2013**, *46*, 375–391. [[CrossRef](#)]
59. Beg, D.; Hladnik, L. Slenderness limit of class 3 I cross-sections made of high strength steel. *J. Constr. Steel Res.* **1996**, *38*, 201–217. [[CrossRef](#)]
60. Xiong, G.; Kang, S.-B.; Yang, B.; Wang, S.; Bai, J.; Nie, S.; Hu, Y.; Dai, G. Experimental and numerical studies on lateral torsional buckling of welded Q460GJ structural steel beams. *Eng. Struct.* **2016**, *126*, 1–14. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.