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Research Paper

Effects of Crossed Stiffeners on the Ultimate Strength of Steel Plate Girders

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Abstract. This research evaluates the flexural behavior of steel plate girders with crossed stiffeners under static loading. Using ABAQUS finite element software, 22 simply supported steel plate girders were modeled and analyzed up to failure. The investigation focused on the effect of several parameters on ultimate strength: stiffener inclination angle (30°, 45°, 60°, 75°), in addition to the yield strength and thickness of the stiffeners, web, and flanges. The results demonstrate a substantial enhancement in the ultimate load as the stiffener inclination angle increased from 30° to 75°, with a considerable rise from 43% to 93% observed, noting that significant improvements were most pronounced beyond 60° inclinations. Furthermore, the ultimate capacity increased by 93-95% through an elevation of yield strength, 93-99% via stiffener thickening, 93-111% with web augmentation, and 93-97% through flange thickening. The comparative performance analysis established that cross-stiffened girders demonstrate marked improvements, with the Pareto-optimal G75D configuration achieving a maximum stiffness with a 38% enhancement and an energy absorption with a 98% increase over the baseline model. This configuration achieved superior integrated performance by maximizing strength, stiffness, and energy absorption, thereby establishing a validated design methodology for enhancing stiffened plate girders in demanding long-span bridge and structural applications.

Keywords: Crossed stiffeners, Steel plate girders, Parametric investigation, Ultimate strength, Finite element analysis.

1. Introduction

Nowadays, steel plate girders have been widely utilized in steel structures and are commonly used with concrete slabs in a wide range of applications, including the construction of bridges and buildings. During the design process of composite bridges, it is common to use slender webs and deep steel girders due to their higher bending strength, lightweight nature, and the maximum flexibility and economy they provide compared to prestressed or post-tensioned concrete girders. To improve overall structural stability, thin-webbed plate girders are conventionally strengthened transversely at equal intervals, thereby separating the web plate into equal panels. Over the past decades, many numerical and experimental investigations have been conducted on I-shaped steel plate girders to improve the web's resistance to shear, bending, and lateral buckling. To achieve economy and efficiency in fabrication, the thin web plate of the girder is often stiffened by longitudinal stiffeners, transverse stiffeners, or inclined ones [1]. The schematic configuration of the steel girder with stiffeners is depicted in Fig. 1. In some cases, slender web panels are stiffened using different methods, such as longitudinal stiffeners to enhance shear and bending resistance. Transverse stiffeners are also installed to increase the strength and stiffness to prevent premature buckling of the web plate [2]. To reinforce the slender web panels of the girder, diagonal or inclined stiffeners are used. This mechanism divides the web panels into triangular sub-panels, leading to a considerable alteration in the shear buckling performance [2]. Web panels are trussed by using oblique intermediate stiffeners throughout the web panel. The stiffeners thus bear a part of the load as well as serving their function of preventing twisting. Oblique stiffeners also possess the benefit of limiting the shear factor without demanding further longitudinal stiffeners [3].

Several studies have been performed to evaluate the effect of longitudinal stiffeners on the ultimate strength of steel plate girders. Truong et al. [4] investigated the impact of utilizing multiple longitudinal web stiffeners (up to four) situated at their optimal location. They employed nonlinear analysis to determine the ultimate flexural strength of steel plate girders experiencing a combination of bending and shear loads. The results showed that a web exposed predominantly to shear or combined shear and bending loads can achieve a strength increase between 8% and 105% by placing no more than four stiffening elements on the web [4]. Loaiza et al. [5] studied the effect of the load-bearing length on the ultimate flexural strength of steel plate girders with longitudinal stiffeners subjected to compressive loads. Their numerical parametric investigation showed that the improvement in ultimate flexural strength is not only influenced by the existence of multiple longitudinal stiffeners but also depends on the bearing length. Moreover, using an upper longitudinal stiffener located near the loaded flange was found to offer good flexural performance and, consequently, an increase in ultimate strength.

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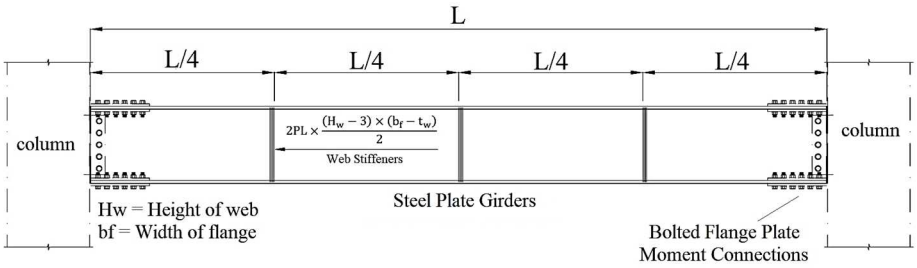


Fig. 1. The schematic configuration of the steel girder with web stiffeners.

Vu et al. [6] employed a gradient-based technique for interior point optimization to determine the optimal placements of multiple longitudinal web stiffeners fitted on one side of the web of steel plates exposed to pure bending. They concluded that the best position for a single longitudinal stiffener is at 0.2D from the compression flange, and for multiple longitudinal stiffeners, it is preferred to place them symmetrically around the horizontal axis of the girder. Loaiza et al. [7] conducted a study to assess the increase in ultimate flexural strength of a thin I-girder subjected to a patch load using open and closed section stiffeners, by testing three distinct stiffener arrangements: namely, stiffeners with a single open section, multiple open sections, and a single closed section. For the optimal girder resistance to patch loading and minimized maximum deflection, they suggested various trapezoidal and flat stiffener configurations. Xu et al. [8] conducted a comprehensive parametric study to examine the effects of web opening details and the cross-sectional area of longitudinal stiffeners in steel beams with unstiffened and longitudinally stiffened web openings. The comparisons indicate that available expressions provide reasonable strength estimations for steel beams with unstiffened web openings.

In parallel studies, researchers have evaluated the effect of transverse stiffeners on the ultimate strength of steel plate girders, demonstrating their significant enhancement potential. Xiao et al. [9] performed a numerical analysis to explore the properties, minimum requirements, and post-buckling capacity of the intermediate transverse stiffener of HSS plate girders. Due to the different strength capacities of HSS and mild steel plate girders, they concluded that the intermediate transverse stiffener in HSS plate girders undergoes considerably more out-of-plane deflection at the ultimate shear resistance than that in mild steel plate girders. Elbanna et al. [10] conducted a numerical study to investigate the behavior of stiffened web panels of a steel plate girder with either transverse or longitudinal stiffeners under various loading conditions. A comprehensive parametric study was conducted to evaluate the effect of geometric parameters, such as: the location of the longitudinal stiffener and the flexural rigidity of the longitudinal and vertical stiffeners on the elastic buckling behavior. The results show that the optimal location for longitudinal stiffeners is at 0.21d from the compression flange. In addition, enhancing the flexural rigidity of the transverse stiffeners leads to a slight improvement in the buckling capacity. Chacón [11] analyzed the mechanical behavior of transversely stiffened plate girders exposed to patch loads and susceptible to shear buckling through numerical parametric analysis. The study found that flexible stiffeners cannot develop anchoring capabilities, either for shear buckling or patch loading. Furthermore, increasing the stiffener thickness increased the girder 's ultimate strength. Moreover, Chacón et al. [12] performed an experimental study on six transversely stiffened plate girders exposed to patch loading. Their findings were supplemented by 44 additional girders that were numerically examined. These girders were tested for their ultimate load capacity and structural response. In their study, they noted that girders with widely spaced transverse stiffeners exhibited a significantly different behaviour from girders that were closely spaced. For the former, a web panel's failure mode was mostly associated with folding, and the flange moment capacity had no effect. For the latter, the behavior seemed to be partly governed by the web, the transverse stiffeners, and the loaded flange. Li et al. [13] studied the influence of reinforcement parameters on the corroded ends of steel girders with multiple transverse web stiffeners. Based on their investigation of the number of end stiffeners and other reinforcement parameters, they proposed a reasonable value range for the reinforced steel plate specifications. Freitas et al. [14] demonstrated through full-scale tests and nonlinear FEM that transversely stiffened plate girders fail by shear buckling, with stiffener forces and principal stress distributions contradicting classical rotated stress field assumptions Nascimento et al. [15] investigated plate girder specimens with varying stiffener configurations. Their results demonstrated that the calculated forces in the intermediate stiffeners were only 50% of the values obtained from the proposed design recommendation process. This indicates that the full capacity of the installed stiffeners was not utilized, as the web experienced buckling failure first.

Alternatively, recent studies have proposed using diagonal and inclined stiffeners to enhance the shear buckling performance of steel plate girders. Azmi et al. [16] conducted an experimental investigation on plate girders with perforated webs accompanied by oblique stiffeners. Ten simply supported specimens were subjected to a static load at the midpoint until failure. Circular web openings of varying diameters were incorporated into the middle web panels of the specimens. The main concern of this study was the influence of the tilt angle on the ultimate load behavior of oblique stiffeners. The results demonstrated that as the angle of oblique stiffeners decreased from 90° to 30°, the ultimate flexural strength significantly increased from 21% to 92%. Yuan et al. [17] studied the shear performance of steel plate girders provided with diagonal stiffeners. Many parameters were examined, including the flexural stiffness of diagonal stiffeners, web slenderness, the web aspect ratio, and the material properties. They concluded that the diagonal stiffeners provide additional out-of-plane restraints for the web plate because they subdivide the plate into triangular subpanels. Hayatdavoodi et al. [18] conducted a numerical and analytical study to investigate the shear capacity of diagonally stiffened steel–concrete composite plate girders. They concluded that the presence of diagonal stiffeners can reduce the buckling effects of the shear panel of girders to some extent and also can increase the elastic shear buckling strength and ultimate shear strength of girders compared to unstiffened thin steel plate girders. Yatim et al. [2] tested thin-webbed plate girders with oblique stiffeners. A static load was applied at mid-span to five simply supported plate girders until failure. They focused on the impact of distinct intermediate stiffeners' tilt angles on the post-buckling response and load-carrying capacity. Findings revealed that decreasing the angle of the oblique stiffeners significantly increased the ultimate capacity by 11% to 50%. Papazafeiropoulos et al. [19] optimized stiffener placement in steel plate girders, demonstrating that closed cross-sections and higher web slenderness maximize buckling resistance. Zhao et al. [20] recently introduced an intelligent optimization framework that combines stochastic stiffener distribution with GA-based topology optimization. This method significantly enhances the buckling resistance of both intact and perforated steel plates through strategic stiffener placement.

Closing the introduction section, one should be noted here that while extensive research has been dedicated to traditional stiffener layouts, these configurations often optimize for a single primary load path (shear or bending) and may not fully exploit potential synergistic effects. This study is founded on the idea that a crossed-stiffener configuration can create a synergistic

stiffening effect, providing multi-directional support that more efficiently confines the web panel and redistributes stresses under complex loading conditions. Although the aforementioned research has evaluated the performance of stiffened steel plate girders across various stiffener configurations, the investigation of crossed-stiffeners remains a critical challenge. Specifically, there is a lack of understanding regarding how the interaction between crossing stiffeners influences the ultimate flexural behavior, failure mechanisms, and overall structural efficiency. The main objective of this study is to examine the behavior of steel plate girders enhanced with novel crossed-stiffeners and to test our central hypothesis regarding their synergistic performance. To the authors' best knowledge, no similar study exists in the technical literature. To achieve this, a finite element (FE) model of crossed-stiffened steel plate girders is first developed and validated against available experimental data from the literature. Subsequently, a parametric study is conducted using twenty-two numerical, simply supported FE models with variable geometric and material properties. Key parameters investigated include stiffener inclination angles, material properties, and thickness variations of the stiffeners, web, and flanges. Crucially, this study is designed not only to quantify the ultimate strength but also to elucidate the underlying failure mechanisms and the interactive behavior of the crossed-stiffener system. Finally, a comprehensive assessment of each parameter's impact on the ultimate strength of crossed-stiffened plate girders is presented to establish a foundational framework for optimizing this innovative configuration.

2. Critical Assessment, Hypotheses, and Limitations

2.1. Advantages and disadvantages of crossed-stiffeners

The utilization of crossed-stiffeners in steel plate girders presents a paradigm shift from conventional stiffening methods, offering distinct advantages alongside certain practical challenges.

2.1.1. *Strong sides (advantages)*

The primary strength of this system lies in its fundamental mechanism. The crossed-stiffener system offers a fundamental performance advantage over conventional stiffeners. Its primary strength is the activation of a truss-action mechanism, where the stiffeners become load-bearing components. This leads to significant improvements in ultimate strength, stiffness, and energy absorption. The configuration allows for more efficient material use, enhancing the shear capacity of plate girders in bridge and building applications.

2.2.2. *Weak sides (disadvantages)*

The main drawback of the proposed system is its increased construction complexity. The fabrication and installation of a network of inclined stiffeners, especially at varying angles, are inherently more complex and potentially more costly than adding standard vertical or horizontal stiffeners. Ensuring precise welding and fit-up for all intersecting stiffeners requires higher craftsmanship. Furthermore, the increased number of elements may complicate internal inspections and maintenance over the structure's lifecycle.

2.2. Research hypothesis and construction of the proposed system

The core hypothesis of this research is that crossed-stiffeners, by functioning as an integral truss system within the web, can fundamentally enhance the flexural behavior of steel plate girders beyond the capabilities of traditional stiffening arrangements. It was hypothesized that parameters such as the stiffener inclination angle, material strength, and component thickness would synergistically control the ultimate strength and structural performance.

The construction of the proposed finite element model, as will be detailed in the next sections, was built upon this premise. Flanges, webs, transverse, and crossed stiffeners were modelled using the shell element (S4R). The interaction between all components was simulated using a Tie constraint to model the contact between them. The models were designed to isolate and investigate the effects of key variables, leading to the creation of distinct groups (A through E) to systematically study inclination angle, yield strength, and the thickness of stiffeners, web, and flange.

2.3. Limitations of the study

While this study provides a validated framework for enhancing the performance of stiffened plate girders, it is bounded by several limitations that outline the scope for future work.

1. Numerical Nature: This research is exclusively a numerical investigation. Consequently, while the findings are robust, they are derived from finite element models and require validation through physical testing. This need is acknowledged in the recommendations, which call for future experimental work to gain a more comprehensive understanding of the behavior."
2. Geometric and Loading Scope: The study was limited to a specific set of girder geometries under static concentrated load applied at the mid-span. Consequently, behaviors under different loading conditions (e.g., distributed or cyclic loading) or in girders with web openings were not investigated.
3. Material and Section Scope: The analysis was confined to standard steel materials and a specific plate girder section. As a result, the effectiveness of crossed-stiffeners on other structural steel sections remains an area for future exploration.
4. Constructability and Cost: This study focuses on the structural performance and does not include a detailed analysis of the economic viability, fabrication costs, or construction sequencing challenges associated with implementing crossed-stiffeners in practical applications.

3. Numerical Modeling Technique and Validation

3.1. Solution method in ABAQUS

The most reliable technique for evaluating the exact performance of steel plate girders is to conduct experimental studies. However, since these are expensive and time-consuming, experiments are not always possible to perform. Therefore, numerical methods are required to extend the experimental work for further investigations. Steel material is considered homogenous, so finite element analysis (FE), is suitable to serve this purpose with less cost and time consumption. All tests presented in this study are only based on the nonlinear finite element simulations via the commercial software ABAQUS [21]. In this section, a description of the used elements, solution procedures, and verification of the previously tested girders is provided. The arc-length method, also commonly known as the Riks method after its development by Riks [22], is an effective numerical technique for solving nonlinear systems of equations in post-buckling analysis. It is capable of tracing equilibrium paths for both stable and unstable post-buckling responses [23–28].

Table 1. The dimensions and cross-sections of the studied girder LS2 [29].

Girder parts	Measurements
	Units /mm
Compression flange	
Width	358.64
Thickness	38.1
Tensile flange	
Width	358.64
Thickness	38.1
Web	
Width	1270
Thickness	4.763
Longitudinal stiffener	
Width	140.20
Thickness	25.4
Transverse stiffener	
Width	76.2
Thickness	19

However, the exact post-buckling problem often cannot be directly inspected because of the discontinuous response at twisting points. Analyzing linear eigenvalues for simple cases may be sufficient for design assessment, but it assumes that geometric and material nonlinearities are not concerns for buckling [23]. In that case, the unstable post-buckling behaviour must be prepared to study the problem further. Eigenvalue buckling analysis is exploited to determine the critical load of structures; it can also investigate the imperfection sensitivity of the structure. The finite element model used in this study has been validated against experimental tests obtained by Cooper and Fielding [29]. Figure 2 shows the adopted girder (known as LS2) used for the validation purpose in this study. The finite element models are constructed with the ABAQUS 2019 [21] software. The web, flanges, longitudinal stiffeners, transverse stiffeners, and bearing stiffeners are modelled using the S4R shell element. The S4R is a general-purpose element with a four-node quadrilateral formulation with reduced integration. The suitable finite element mesh size was found to be equal to 50 mm for the verified models, after a series of convergence studies involving mesh sizes of 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm, as illustrated in Fig. 3(a). The number of nodes was 8809 while the number of elements was 8653. The geometric characteristics of the original girder LS2 used in this study are listed in Table 1. The yield stress of the flange f_{yf} is equal to 206 MPa while the yield stress of the web f_{yw} is 275 MPa. In addition, the yield stress of the longitudinal stiffeners with a width of 5.5 inches is equal to 206 MPa, and that for a width 4 inches is considered to be 275 MPa. The modulus of elasticity E is set to 200 GPa. The length of the original girder LS2 equals to 8382 mm (330 in). The steel material of the girder was simulated using the bilinear stress-strain relation with strain stiffening according to Eurocode 3 [30].

3.2. Loading system, boundary conditions and geometric imperfection patterns

In order to define boundary conditions of the test, the upper flange surface is coupled to a reference point at the mid-length of the girder. Utilizing a coupling constraint, this reference point is constrained to the surface. Figure 3(b) depicts the applied boundary conditions for the studied girder model. The load is applied using a vertical displacement-control method. At its ends, the girder is deemed to be simply supported by rollers and hinged supports. To replicate the actual test, the girder was restrained from lateral movement in any direction by two lateral support pipes, while still being permitted to move vertically under the applied load.

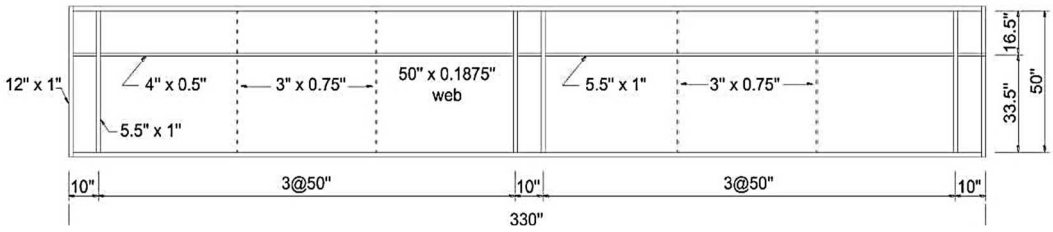
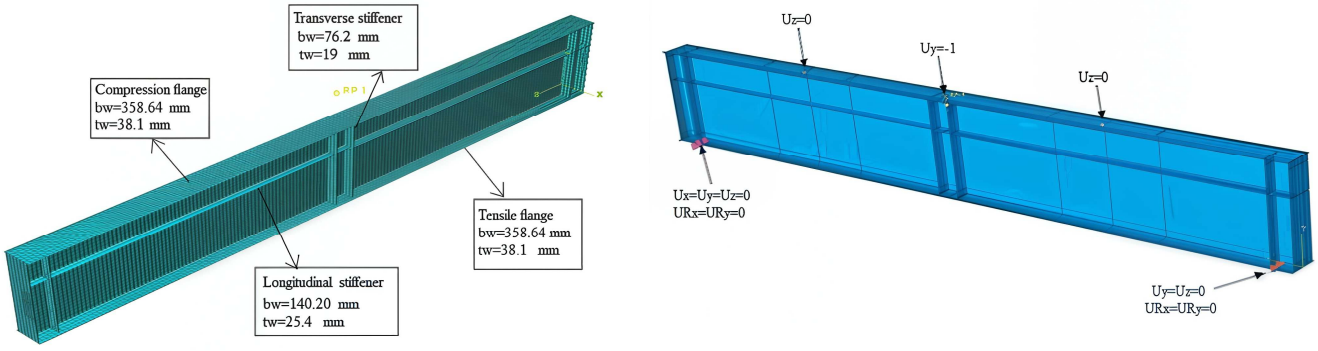


Fig. 2. Geometry of considered girder LS2 from experimental study [29] (dimensions in inches).



(a) (b)

Fig. 3. Finite element model, (a) the considered mesh of LS2 model, (b) Boundary conditions and loading of the validated girder SL2 based of Truong et al. [4].

Table 2. Geometric details of all the case studies of steel plate girders with crossed-stiffener.

Group	Girder	f_y (MPa)	t_s crossed (mm)	b_s crossed (mm)	t_w (mm)	t_f (mm)	Angle (Degree)
-	G1	250	-	-	4.763	38.1	-
A	G30A	250	25.4	140.2	4.763	38.1	30
	G45A	250	25.4	140.2	4.763	38.1	45
	G60A	250	25.4	140.2	4.763	38.1	60
	G75A	250	25.4	140.2	4.763	38.1	75
B	G30B	350	25.4	140.2	4.763	38.1	30
	G45B	350	25.4	140.2	4.763	38.1	45
	G60B	350	25.4	140.2	4.763	38.1	60
	G75B	350	25.4	140.2	4.763	38.1	75
C	G30C	250	38.1	140.2	4.763	38.1	30
	G45C	250	38.1	140.2	4.763	38.1	45
	G60C	250	38.1	140.2	4.763	38.1	60
	G75C	250	38.1	140.2	4.763	38.1	75
D	G30D	250	25.4	140.2	5.763	38.1	30
	G45D	250	25.4	140.2	5.763	38.1	45
	G60D	250	25.4	140.2	5.763	38.1	60
	G75D	250	25.4	140.2	5.763	38.1	75
E	G30E	250	25.4	140.2	4.763	39.2	30
	G45E	250	25.4	140.2	4.763	39.2	45
	G60E	250	25.4	140.2	4.763	39.2	60
	G75E	250	25.4	140.2	4.763	39.2	75

In most steel structure members, initial engineering defects occur during transportation, manufacturing, and handling processes. Geometric imperfections can be found on the inner or outer surfaces of metal structural members. Perturbations in the geometry usually lead to these imperfections. ABAQUS software [21] introduces three ways to represent geometric imperfections: 1) linear superposition of buckling eigenmodes, 2) using the displacements of a static analysis, and 3) by directly specifying the imperfection values based on the node number. In this study, the initial geometric imperfections were modelled in two steps: first, eigenmodes were established using an eigenvalue buckling analysis; second, nonlinear plastic analyses used these eigenmodes as initial shapes. The buckling modes are assumed to be the same as the failure modes detected in the original samples, and their amplitude is assumed to be equal to D/200 as described in Eurocode 3 [30].

3.3. Validation of the proposed finite element model

The comparison between the finite element and the experimental load-displacement response is illustrated in Fig. 4. The predicted findings by the proposed FE model are in acceptable agreement with the experimental test results, as shown in Fig. 4. The finite element ultimate load is 1515.58 kN and was slightly higher than the experimental capacity of 1457.884 kN. Finite element simulations predicted an ultimate load that was less than 5% different from the experimental value. Furthermore, the total difference between the experimental and the modelled girder was less than 10% in displacement. Both of the tested and verified models showed the same behaviour in terms of stiffness and ductility from the initial stage of loading until failure. Moreover, both models exhibited the same energy absorption of energy as depicted in Fig. 4.

4. Structural Characteristics of the Plate Girders

4.1. Case study of models

Parametric studies considered in this study are conducted to inspect the behavior of steel plate girders provided with crossed stiffeners undergoing combined shear and bending. In this section, finite element models have been analysed to explore the influence of using crossed-stiffeners on the ultimate strength of the steel plate girders. The models were classified into five groups: A, B, C, D, and E, as shown in Table 2. The structural geometric details of all case studies considered for the parametric study are similar to the validated baseline numerical model LS2 (Table 1). The length and depth of all models are equal to those of the baseline model, at 8382 mm and 1270 mm, respectively. However, the difference is the addition of the crossed-stiffeners.

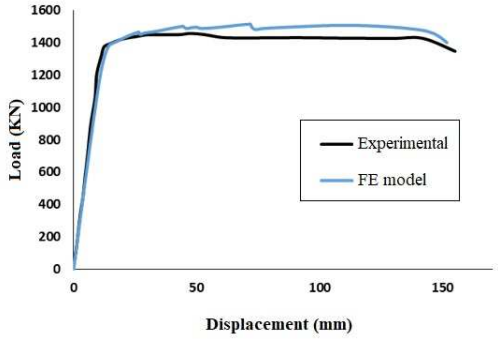


Fig. 4. Comparison between the FE model and the experimental results of Cooper and Fielding [29].

Table 3. Mesh size and Number of elements for each girder.

Group	Girder	Mesh size (mm)	Number of elements	Number of nodes
-	G1	50	7947	8118
A, B, D, C, E	G30 A, B, C, D, E	50	9143	9261
	G45 A, B, C, D, E	50	9030	9151
	G60 A, B, C, D, E	50	8393	8505
	G75 A, B, C, D, E	50	5360	5461

For comparison purposes, girder G1 was assumed as a control girder and is completely similar to the original validated girder LS2, except it does not have longitudinal stiffeners, as shown in Fig. 5(a). For instance, the structural geometric details for the four groups of models A, B, C, D are illustrated in Fig. 5(b). In addition, the finite element model for group E is also depicted in Fig. 6. It is worth mentioning that Young's modulus and Poisson's ratio of the steel material were considered as 200 GPa and 0.3, respectively Additional information including mesh sizes and element types of the case study girders are presented in Table 3.

4.2. Variable test parameters

To assess the influence of various crossed stiffeners on steel plate girder strength, parametric variations were established across distinct model groups. As shown Fig. 5(a), the benchmark specimen (G1), lacking stiffeners and possessing a yield stress f_y of 250 MPa, serves as the control. Group A comprises four girders (G30A, G45A, G60A, G75A) featuring stiffeners inclined at 30°, 45°, 60°, and 75° angles, all with f_y= 250 MPa (Table 2 and Fig. 5(b)). Group B models (G30B, G45B, G60B, G75B) share the same angular variations but employ a higher stiffener yield strength f_y of 350 MPa, as presented in Table 2 and Fig. 5. Group C (G30C, G45C, G60C, G75C) utilizes f_y= 250 MPa but increases stiffener thickness t_s from 25.4 mm to 38.1 mm as illustrated in Table 2 and Fig. 5. Similarly, Group D (G30D, G45D, G60D, G75D) maintains f_y= 250 MPa while augmenting web thickness t_w from 4.763 mm to 5.763 mm (Table 2 and Fig. 5). Finally, Group E (G30E, G45E, G60E, G75E) tests f_y = 250 MPa with an increased flange thickness t_f, raised from 38.1 mm to 39.2 mm, as presented in Table 2.

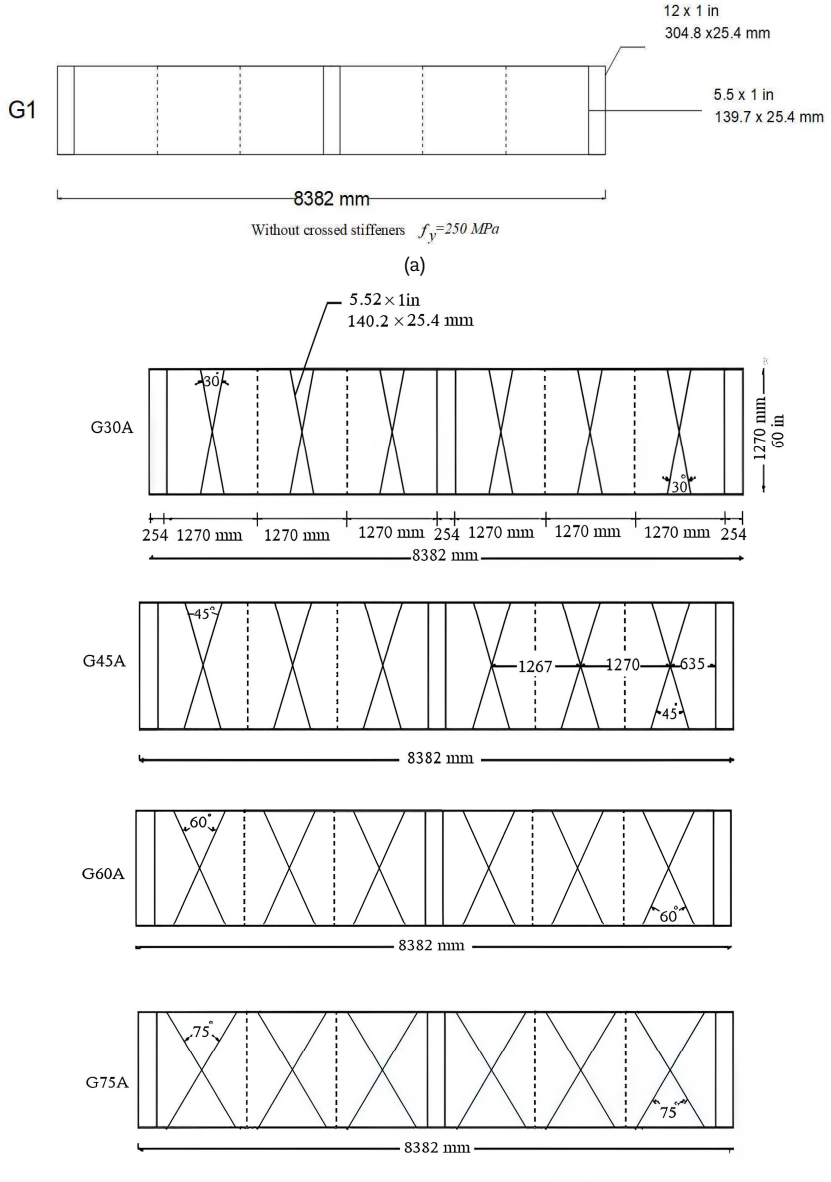


Fig. 5. Geometric configuration of all studied girders, (a) Details of the reference baseline girder, (b) Details of the group models A, B, C and D.

5. Key Mechanisms Governing Parametric Performance

Finite element analysis (FEA) provides comprehensive insights into stress and strain distributions within complex structures, information often challenging to obtain experimentally. This capability enables parametric numerical studies to significantly enhance structural design efficiency. This study employs the software ABAQUS [21] to develop sophisticated three-dimensional nonlinear finite element models. Given the novel nature and limited empirical data on crossed stiffeners, a rigorous numerical investigation is essential to validate their effectiveness, structural capacity, and real-world applicability. Specifically, the ultimate load performance of steel plate girders incorporating these stiffeners was examined. As mentioned in the previous section, five distinct groups were analyzed, each comprising four girders with stiffeners inclined at 30°, 45°, 60°, and 75°. The parametric study quantifies the influence of key variables: material yield strength f_y, stiffener thickness t_s, web thickness t_w, and flange thickness t_f.

5.1. Effect of using crossed-stiffeners

Group A comprises four girders incorporating stiffeners inclined at 30°, 45°, 60°, and 75° relative to the horizontal axis. Load-deflection behavior for all models is depicted in Fig. 7, while Table 4 quantifies ultimate load, failure displacement, and load enhancement. Girder G75A exhibited a marked increase in ultimate capacity compared to its counterparts G60A, G45A, G30A, and the control girder G1. This performance gain correlates with the maximal inclination angle (75°), consistent with the truss-action mechanism reported by Azmi et al. [16], wherein oblique stiffeners mobilize additional load-bearing pathways.

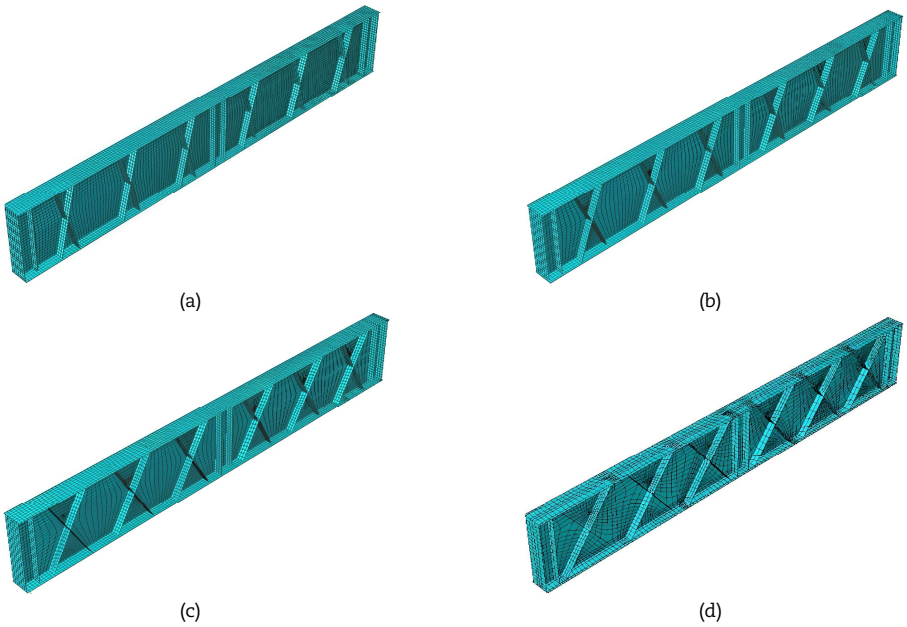


Fig. 6. Finite element mesh for group model E, (a) G30E, (b) G45E, (c) G60E, (d) G75E.

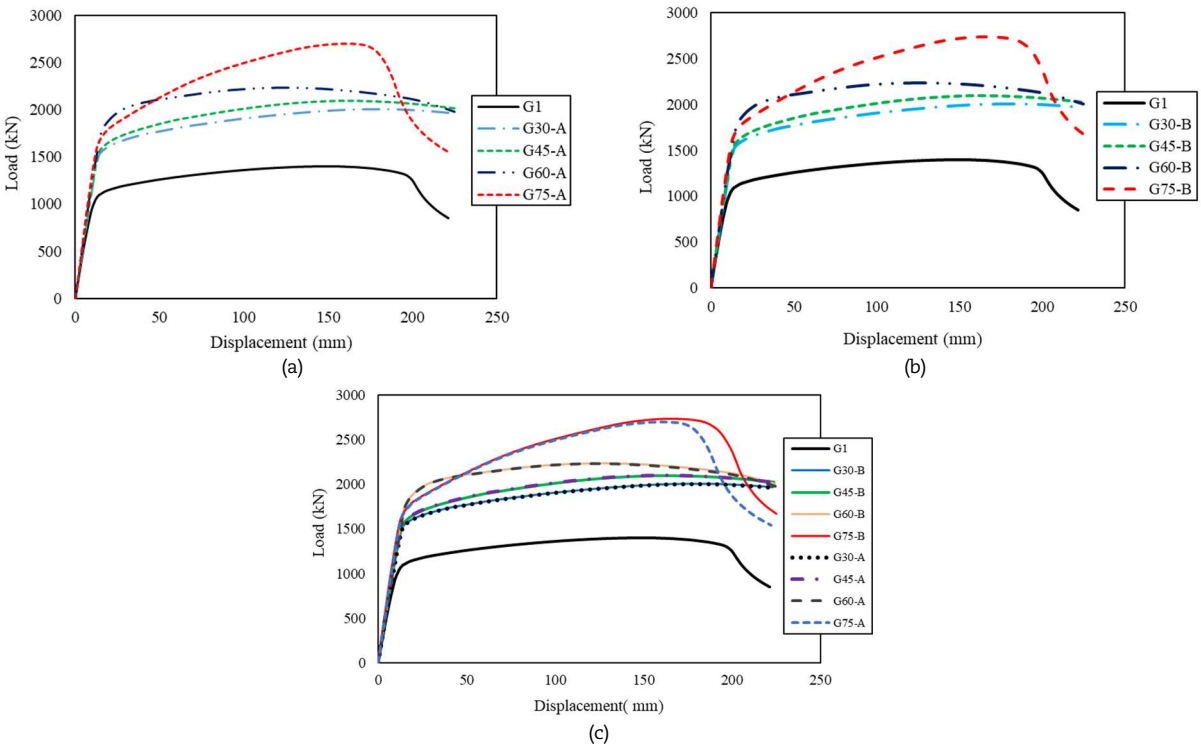


Fig. 7. Comparison of load-deflection curves for girder groups A and B, (a) Group A, (b) Group B, (c) Groups A and B.

Table 4. Comparison of ultimate loads for all girders Groups.

Girder	Ultimate load Pu (kN)	Displacement Du (mm)	Ultimate load increase (%)
G1	1399	147.4	-
G30 A	2006	178.5	43
G45 A	2098	162.4	49
G60 A	2230	162.4	59
G75 A	2703	161.1	93
G30 B	2008	178.6	43
G45 B	2099	160.7	50
G60 B	2233	123.0	60
G75 B	2734	166.0	95
G30 C	2040	194.3	46
G45 C	2114	168.5	51
G60 C	2250	132.2	61
G75 C	2781	174.4	99
G30 D	2292	161.3	64
G45 D	2412	155.1	72
G60 D	2540	146.6	81
G75 D	2951	170.1	111
G30 E	2037	178.6	46
G45 E	2131	162.5	52
G60 E	2276	126.6	63
G75 E	2761	157.7	97

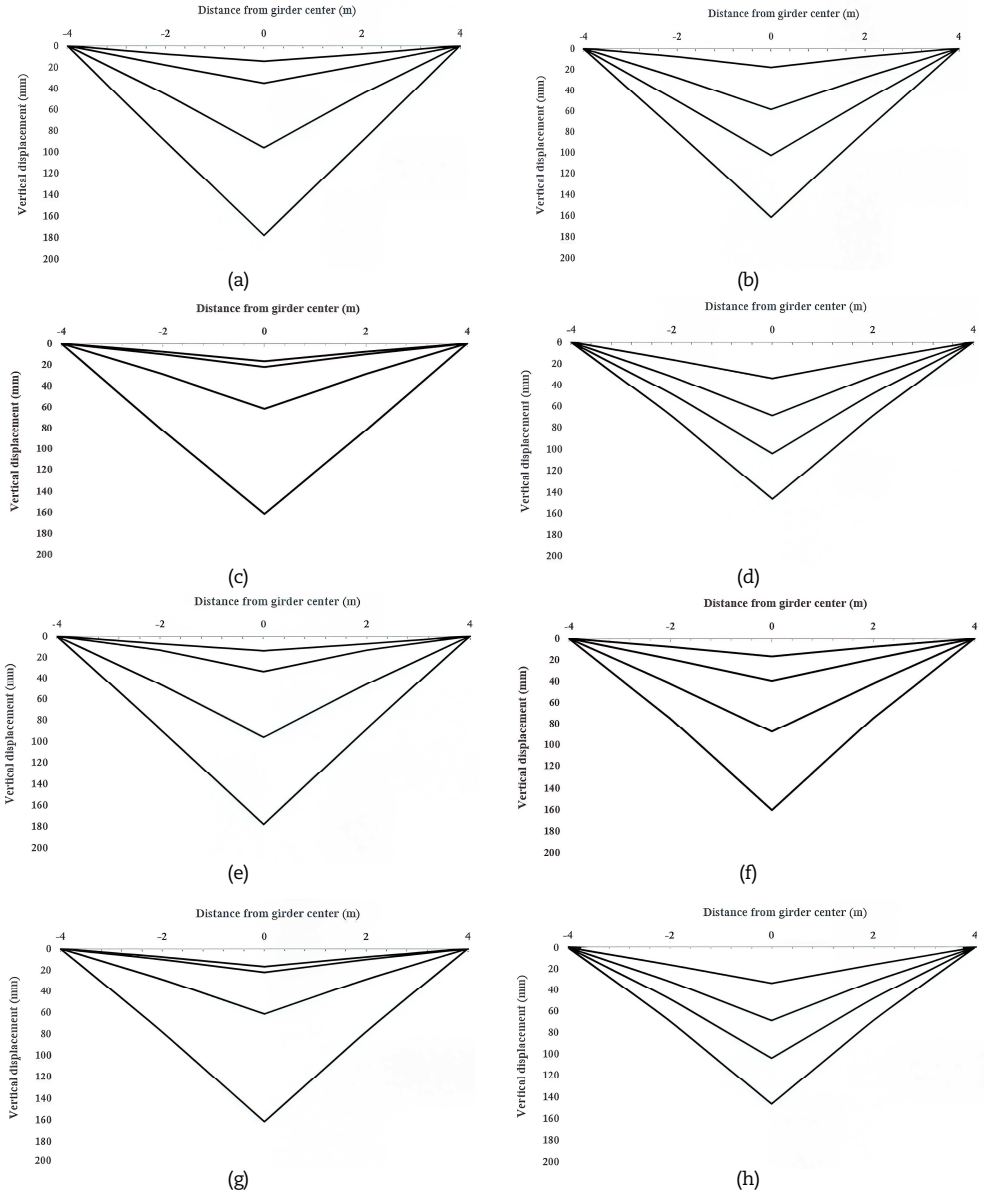


Fig. 8. The vertical displacement profile for girder groups A and B, (a) G30 A, (b) G45 A, (c) G60 A, (d) G75 A, (e) G30 B, (f) G45 B, (g) G60 B, (h) G75B.

All specimens demonstrated comparable elastic flexural responses, evidenced by parallel initial slopes in Fig. 7. For instance, Fig. 8 shows the vertical displacement histories and failure mode visualizations from initial loading to ultimate failure. As shown in Fig. 9, post-failure analysis reveals von Mises stress concentrations and plastic strain localization initiating between stiffener intersections and propagating along the web panel.

Regarding Group B, four girders with identical 30°–75° stiffener inclinations were analyzed under elevated stiffener yield strength f_y= 350 MPa. Load-deflection characteristics (Fig. 7(b)) and ultimate loads (Table 4) confirm that G75B achieved superior ultimate load resistance relative to other Group B specimens and the baseline G1. This enhancement is attributed to the synergistic effects of high inclination angles and increased stiffener material strength, which augment force redistribution through truss-like behavior [16, 31]. It is worth mentioning that elastic-stage flexural rigidity remained consistent across the group as shown in Fig. 7. Displacement profiles are provided in Fig. 8. Stress contours and plastic strain distributions elucidate failure initiation at stiffener-web junctions. Figure 7(c) demonstrates significantly higher ultimate loads for Group B specimens relative to their Group A counterparts at equivalent inclination angles. This performance differential (e.g., G75B vs. G75A) underscores the critical influence of stiffener yield strength on global girder capacity. The elevated f_y enhances stiffener contribution to load transfer mechanisms, delaying instability and increasing structural reserves.

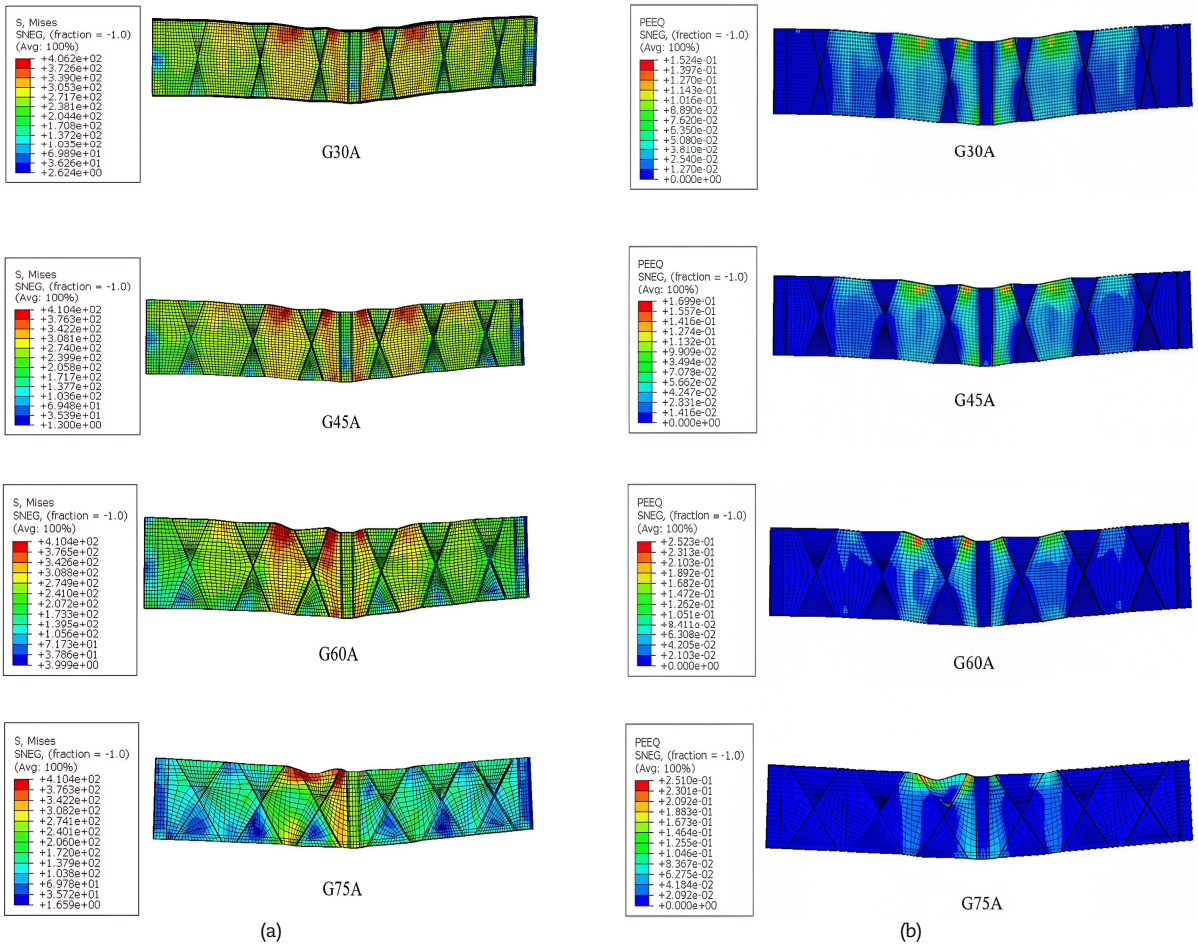


Fig. 9. The Von Mises stresses and plastic strain contour for girders group A, (a) Von Mises stresses, (b) Plastic strain contour.

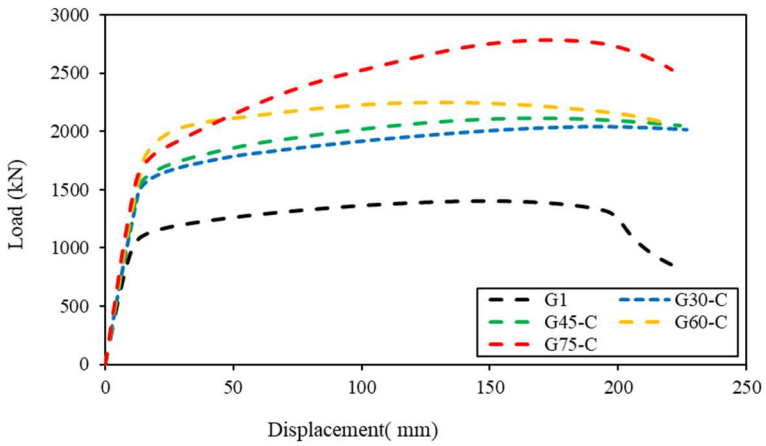


Fig. 10. Load-displacement response for girders in Group C.

5.2. Effect of thickness of crossed stiffeners on ultimate strength of steel plate girders

Group C evaluates four girders with stiffeners inclined at 30°, 45°, 60°, and 75°, featuring an increased stiffener thickness compared to Group A. As illustrated in Fig. 10 and Table 4, load-deflection responses indicate that specimen G75C achieved a substantially higher ultimate load capacity: 23.6% higher than G60C (2250 kN), 31.6% higher than G45C (2114 kN), 36.3% higher than G30C (2040 kN), and 98.8% higher than the control girder G1 (1399 kN), demonstrating its exceptional performance relative to its counterparts. This enhancement correlates directly with the maximum inclination angle (75°), consistent with the truss-analogy principle [16, 31] wherein inclined stiffeners mobilize additional load-transfer mechanisms. All specimens exhibited comparable elastic-stage flexural stiffness, evidenced by initial curve slopes in Fig. 10. Post-failure analysis also reveals von Mises stress concentrations and plastic strain localization initiating at stiffener-web intersections. As evidenced in Table 4, the ultimate load is substantially greater for Group C specimens relative to their Group A counterparts at equivalent inclination angles. Increasing the stiffener thickness (t_s) enhances out-of-plane rigidity, mitigates local buckling, and promotes more efficient load redistribution through truss-action behavior. Crucially, cross-group comparison reveals general capacity augmentation across all inclinations, highlighting thickness-dependent stabilization of web-stiffener interfaces.

5.3. Effect of thickness of the web and flange on ultimate strength of steel plate girders

This section examines two distinct girder configurations: Group D, featuring web thickness variations, and Group E, incorporating flange thickness modifications, both comprising stiffener inclination angles of 30°, 45°, 60°, and 75°. Figure 11 compares the performance of girders in Groups A through E across these stiffener inclination angles of 30°, 45°, 60°, and 75°. The identical response of 30° inclination specimens (G30-A to G30-E) confirms the stiffener angle as the primary governing parameter. At low angles, the underdeveloped truss mechanism renders the girder insensitive to other modifications. However, at higher angles (≥ 60°), the activated truss-action enables synergistic benefits from secondary parameters. Notably, increasing web thickness (Group D) proves to be the most effective secondary enhancement, as it directly strengthens the primary shear-carrying component. This establishes that while the inclination angle dictates the fundamental efficiency, strategic web thickening provides the most significant complementary gain in ultimate capacity. As clearly shown in Fig. 11, the load-deflection responses demonstrate that steeper stiffener angles (e.g., 75° in G75D/G75E) substantially enhance ultimate load capacity, owing to optimized force redistribution through truss-action mechanics. While both groups exhibited similar elastic flexural stiffness, failure modes diverged: Group D failed via shear-flexural buckling due to web slenderness, whereas Group E's thicker flanges increased bending resistance, delaying flexural-torsional buckling. Furthermore, comparative analyses confirmed that Group D's thicker webs improved shear buckling resistance, while Group E's flange augmentation elevated bending capacity. Both groups ultimately exhibited buckling between stiffeners, with stress and strain distributions underscoring the critical role of sectional thickness in governing failure modes.

5.4. Effect of aspect ratios

Consistent with the previous section, all girders maintain identical length, depth, and flange width dimensions corresponding to test specimen LS2 in Cooper and Fielding [29]. The investigation focused on three primary parameters: (1) web depth to thickness ratio (D/t_w = 267 and 220), (2) flange width to thickness ratio ($b_f/2t_f$ = 5 and 9), and (3) stiffener width to thickness ratio (b_s/t_s = 4 and 6). These variables were systematically adjusted across case studies to assess their structural effects. To mitigate local buckling risk, the stiffener's width-to-thickness ratio (b_s/t_s) was designed to satisfy AASHTO LRFD [32] requirements. Table 5 presents the ultimate load capacities (P_u) for girders with varying stiffener configurations and aspect ratios. Stiffener inclination angle significantly enhances performance at constant ratios ($b_f/2t_f$ = 9, D/t_w = 267, b_s/t_s = 6), where increasing the angle from 30° to 75° increases capacity by 34.7%, as seen in a comparison of G30A and G75A. For girders G75D and G75A, reducing the web depth-to-thickness ratio from 267 to 220 achieves a 9.2% higher capacity at identical angles.

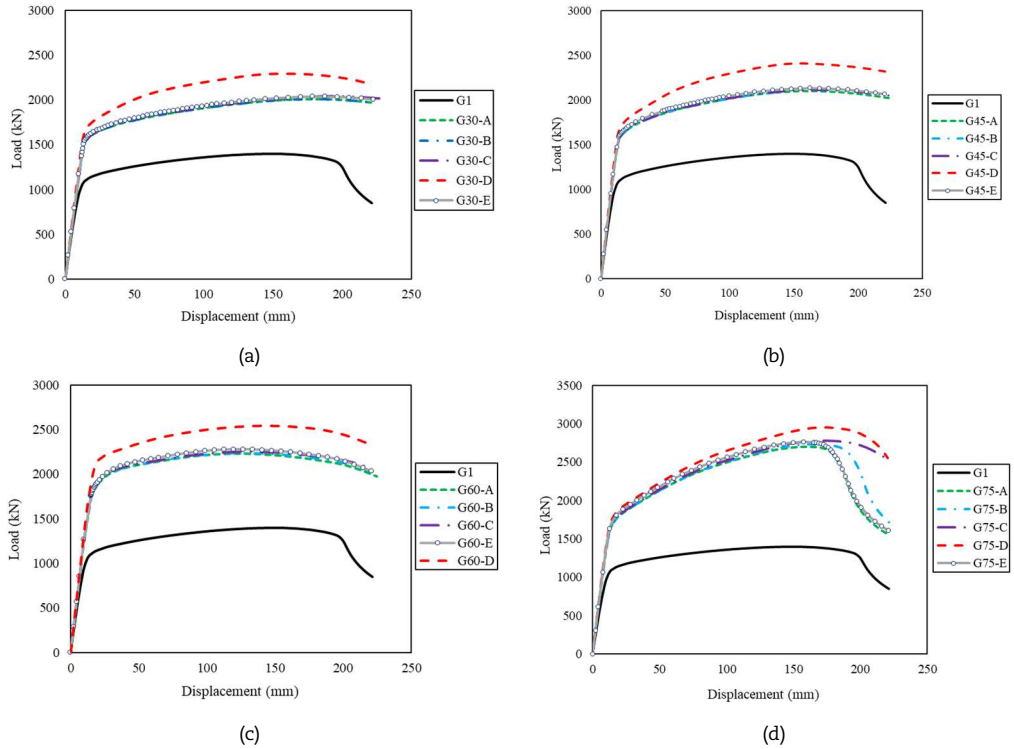


Fig. 11. Load-displacement response of girder, (a) G30-Series girders, (b) G45-Series girders, (c) G60-Series girders, (d) G75-Series girders.

Table 5. Ultimate loads of the girder for different aspect ratios.

Girder	$b_f/2t_f$	D/t_w	b_s/t_s	Ultimate load Pu (kN)
G30A	9	267	6	2006.92
G45A	9	267	6	2098.08
G60A	9	267	6	2230.92
G75A	9	267	6	2703.49
G30B	9	267	6	2008.09
G45B	9	267	6	2099.35
G60B	9	267	6	2233.62
G75B	9	267	6	2734.58
G30C	9	267	4	2040.98
G45C	9	267	4	2114.68
G60C	9	267	4	2250.17
G75C	9	267	4	2781.08
G30D	9	220	6	2292.99
G45D	9	220	6	2412.01
G60D	9	220	6	2540.69
G75D	9	220	6	2951.19
G30E	5	267	6	2037.5
G45E	5	267	6	2131.96
G60E	5	267	6	2276.65
G75E	5	267	6	2761.41
G1	9	267	-	1399.95

It also can be obvious from Table 5 that reducing the stiffener width-to-thickness ratio from b_s/t_s = 6 to 4 yields 1.7% improvement, as seen in the increase from 2734.58 kN for G75B to 2781.08 kN for G75C. Similarly, a flange width-to-thickness ratio reduction from $b_f/2t_f$ = 9 to 5 demonstrates limited impact, with G30A at 2006.92 kN compared to G30E at 2037.5 kN, representing a 1.5% increase. It is worth mentioning that the unstiffened control baseline G1, with a capacity of 1399.95 kN, underscores the critical role of stiffeners, exhibiting 43% to 111% lower capacity than optimized configurations.

Fig. 12. The initial stiffness of crossed-stiffed plate girders.

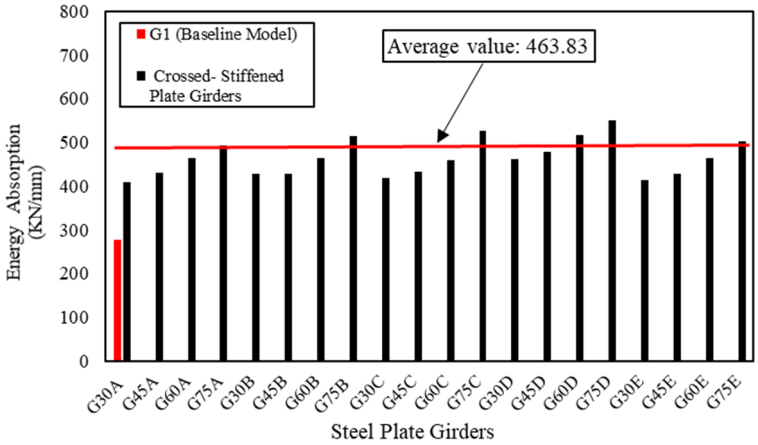


Fig. 13. The energy absorption of crossed-stiffed plate girders.

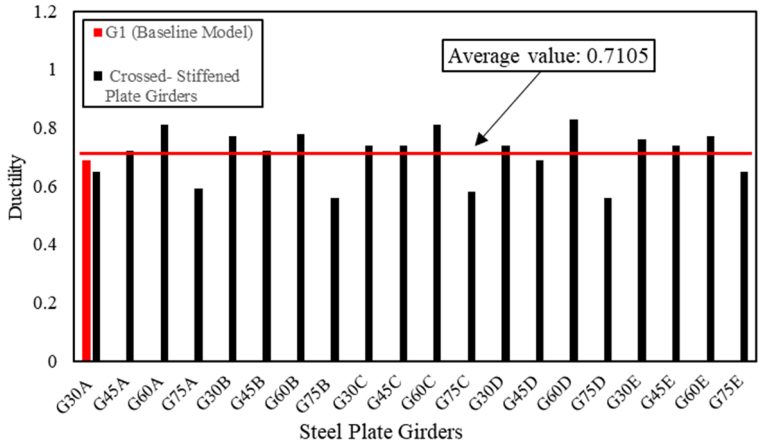


Fig. 14. The ductility distribution of crossed-stiffed plate girders.

5.5. Initial stiffness, energy absorption, and ductility of girders

The comparative performance analysis, as demonstrated in Figs. 12-14, establishes that cross-stiffened girders demonstrate marked improvements over the control specimen (G1). Figure 12 exhibits a consistent 24% mean enhancement across all stiffened configurations, with the G75D specimen achieving a maximum stiffness of 132 KN/mm, which is 38% superior to the baseline model G1. As shown in Fig. 13, energy absorption capacity presents even more compelling evidence, with the area under the curves expanding progressively with increasing stiffener inclination. The energy absorption capacity of each studied girder reveals that stiffened specimens absorb 65% more energy on average, maximizing at G75D's remarkable 550 kN/mm, which is 98% above the baseline model G1. This enhancement follows an observable trend, where the use of crossed stiffeners significantly improves ultimate capacity beyond 60° inclinations. As illustrated in Fig. 14, the ductility distribution confirms that the enhanced structural strength is achieved without sacrificing deformation capacity. While maintaining a comparable ductility factor to the control specimen G1, the post-yield response demonstrates 15-20% wider hysteresis bands, indicative of superior energy dissipation characteristics. Notably, specimens with 75° stiffener inclination exhibit marginally lower ductility, with a value of 0.59, which is offset by their significantly improved stiffness and energy absorption capabilities. To conclude this section, one can infer that stiffener inclination angle governs performance enhancements. The G75D configuration represents the Pareto optimum, simultaneously maximizing stiffness, energy absorption, and maintaining adequate ductility- a tripartite enhancement unachievable in unstiffened designs.

6. Conclusion

In this paper, the effects of stiffener inclination angle, material yield strength, and thickness of crossed stiffeners, web, and flange on the ultimate strength of steel plate girders with crossed-stiffeners are investigated. The results demonstrate that by increasing the stiffener inclination angle from 30° to 75°, a significant improvement of up to 93% is achieved in the ultimate load-carrying capacity, with the most substantial gains occurring beyond 60°. The corresponding 75° angle provides the best performance among all groups. This increasing inclination systematically redistributes load through truss-action mechanisms; while strategic thickening of web, flange, and stiffener components thus synergistically enhances structural integrity. The comparative performance analysis confirms that cross-stiffened girders offer marked improvements over conventional designs. The G75D specimen achieved a maximum stiffness of 132 kN/mm and a remarkable energy absorption of 550 kN/mm, representing improvements of 38% and 98%, respectively, over the baseline. Furthermore, material and geometric modifications substantially improved the performance of steel plate girders with crossed-stiffeners. Yield strength elevation from 250 to 350 MPa increased ultimate capacity by 95% while thickness augmentations in stiffeners, web and flange enhanced capacity by up to 99%, 111% and 97%, respectively, compared to the baseline unstiffened model. The analysis also revealed that critical slenderness ratios including the web depth-to-thickness ratio, flange width-to-thickness ratio and stiffener width-to-thickness ratio, are inversely proportional to ultimate strength. It was also found that this enhanced structural strength is achieved without sacrificing deformation capacity, with post-yield responses demonstrating 15-20% wider hysteresis bands, indicative of superior energy dissipation. The Pareto-optimal G75D configuration achieves unprecedented holistic performance, simultaneously maximizing strength, stiffness, and energy absorption through controlled ductility, a transformative capability unachievable in conventional unstiffened systems. This configuration represents the Pareto optimum, delivering a tripartite enhancement in stiffness, energy absorption, and adequate ductility. These findings provide a validated framework for enhancing the performance of stiffened plate girders in practical bridge and building applications where weight-to-strength efficiency is paramount.

Author Contributions

The authors confirmed the contribution to this article as follows: A.B. Mohsin Alshaher: Software, Validation, Formal analysis, Data Curation. A. Rezaeian: Conceptualization, Methodology, Writing - Review & Editing, Supervision. M. Labibzadeh: Conceptualization, Methodology, Review & Editing, Supervision. S. Farahani: Methodology, Original draft preparation, Investigation, Writing - Review & Editing, Software. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

The datasets are available from the corresponding author on reasonable request.

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