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Yielding Behaviour of Steel Beams as a Result of the Shape of the Strands' Fixity Profile

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Keywords:
Eccentricity location; Fixity of strand; Profile strand; Pre-stress; Yielding behavior.

Highlights:

- *To provide a better understanding of how pre-stressed strands affect the behaviour of steel beams during the yielding stage.*
- *Study the effect of the shape of the strand path on the behavior of steel beams up to the yield load.*
- *Study of the increase in eccentricity on the ultimate load and yield load of the tested steel beams.*

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Abstract: Seven simply supported steel beams were built and tested to provide a better understanding of how prestressed strands affect the steel beams' behavior during the yielding stage. Steel beams had identical clear span lengths (2.85 m) and gross-section areas (3268 mm^2). The strengthened sample was constructed using two external strands. The steel beams were divided into two types based on whether the exterior strand's eccentricity was present or not. One of the steel beams serves as a reference. The remaining six steel beams were strengthened by external strands, which were divided according to the eccentric positions of the strands with the jacking stress (fpj = 815 MPa). It was found that strand eccentricity increase increased the ultimate load and yielding of tested strengthened beams. Also, the percentage of yielding to ultimate load ratio (Py/Pu) increased with the strand eccentricity. Finally, compared to the reference beam, the yielding strain positions for all tested beams shifted from the bottom to the top region, and all strain in the top and bottom zones were enhanced compared to the reference due to the external prestress strand, which improved the bottom and top flanges and the resistance of the web under the applied load.

سلوك الخضوع للعتبات الفولاذية نتيجة لشكل مسار تثبيت السلك مسبق المجهد

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الخلاصة

تم بناء واختبار سبع عتبات فولاذية ذات اسناد بسيط من أجل فهم أفضل لكيفية تأثير اسلاك الإجهاد المسبق على سلوك العتبات الفولاذية خلال مرحلة الخضوع. تمتلك العتبات الفولاذية أطوالًا متساوية (طول العتبة= ٢,٨٥ م(ومساحات مقطعية ثابتة (٣٢٦٨ ملم٢)، وتم إنشاء العتبات المقواة بالأسلاك الفولاذية مسبقة الاجهاد باستخدام سلكين خارجيين. تنقسم العتبات الفولاذية إلى نوعين بناءً على ما إذا كان الانحراف المركزي للسلك الخارجي موجودًا أم لا. تعمل إحدى العتبات الفولاذية بمثابة عتبة مرجعية. وتم تقوية العتبات الفولاذية الستة المتبقية بواسطة اسلاك خارجية مسبقة الجهد، والتي تم تقسيمها وفقًا للمواضع اللامركزية للأسلاك مع إجهاد الرفع يساوي fpj = 815 MPa. لقد وجد أن زيادة انحراف السلك أدت إلى زيادة الحمل النهائي وإجهاد الخضوع العتبات المقواة المختبرة. كما أن نسبة الخضوع إلى نسبة الحمل النهائي (Py/Pu) تزداد كلما زاد الانحراف اللامركزي في السلك. أخيرًا، بالمقارنة مع العتبة المرجعية، تنتقل مواضع انفعال الخضوع لجميع العتبات المختبرة من المنطقة السفلية إلى المنطقة العلوية، وحصل تحسن في الانفعال في المنطقة العلوية والسفلية مقارنةً في جميع العتبات الست بالمقارنة مع العتبة المرجعية بسبب السلك الخارجي مسبق الجهد، وهو ما أدى الى تحسن الشفة (flange) السفلية والعلوية ومقاومة الجذع (Web) تحت الحمل المسلط.

الكلمات الدالة: سلوك الخضوع، ثبات السلك (الظفيرة)، مسار السلك (الظفيرة)، موقع الحمل اللامركزي.

1.INTRODUCTION

Steel is the most significant material for constriction, with strength up to 10 times that of concrete. Steel also has the advantage of being easier to manufacture. Due to its high strength-to-weight ratio, high elastic modulus, high strength-to-ductility ratio, high seismic energy absorption, and ease of recycling. Hence, with the low self-weight, the steel frame's dimensions can be decreased [1]. A technique known as prestressing is utilized to enhance the efficiency and toughness of steel members to add internal stress to the steel sections [2,3]. A post-tension technique called the exterior strand's eccentricity involves attaching the exterior strand's eccentricity to the outside of a steel section and transferring forces to the structural parts in the diverters, plates, and anchorages. It is frequently employed on bridges and other structures that have exceeded the yield point and are bearing greater weight than expected; it is employed to repair and strengthen important components [4]. The exterior strand is fastened on the steel beam model through the end steel plate. Depending on the bending moments' diagrams and the applied loads, an infinite number of diverters can position the exterior strand form on the inner length and aid in designing a straight, draping, or parabolic scheme profile [5]. Dabaon and Omnia, 2005 presented the exterior strand's eccentricity. It was pulled out while simultaneously tensioning the strand from one end, as shown in Fig. 1. Wu and Bowman (2000) reported that greater attention must be paid to balancing the jacking force in the exterior strand's eccentricity to protect the tested beam from biaxial bending and distortion [6].

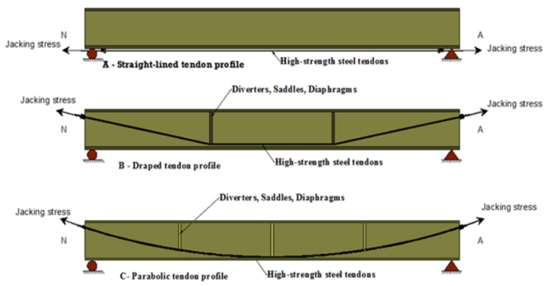

Fig. 1 Strengthening by External High-Strength Steel Strands [5].

The yielding behavior of steel beams has been extensively studied during the last twenty years due to their vital function in construction [6-8]. Daly and woodward [9] studied External post-tensioning reinforced concrete structures without demolition or restoration, boosting load-bearing capacity and lifespan. To assess the external prestressing strands effects as reported in litterture [10-12] The Standard Specification for Steel Strand, have been reported for prestressed concrete outlines the necessary requirements for the strength, dimensions, and testing of seven-wire strands used in prestressed concrete, ensuring reliable performance in construction applications [13-15]. Similarly, Mahmoud [16] studied the strengthening of I-section steel beams using prestressing strands, and Al-Ridha [17] investigated the effect of Carbon Fiber Reinforced Polymer (CFRP) laminates on the flexural strength behavior of steel beams, with and without end anchorage plates. Yousif et al. [18] analyzed the effect of prestressing strands on the shear behavior of steel beams to enhance structural performance, along with the biological standardization reported by the World Health Organization [19]. Mahmoud et al. [20], examined 13 supported steel beams. These beams had the same clear span length, steel section, and two exterior preconditioning strands. The tested beams were divided into two groups; one had a single steel beam that acted as a reference, and the other was made up of steel beams that strengthened with external prestressing strands and divided into two groups by jacking stress. Throughout the test, the load-deflection curves for beams reinforced with outer prestressing strands were stiffer than the reference beams. However, with jacking tension at constant eccentricity, the curves slightly improved. In addition, maximum applied stress at midspan was elevated somewhat by eccentricity. Rasheed et al., investigated a strengthened steel beam section under eccentric loadings. The authors concluded that the ultimate load capacity percentage increased with increasing the eccentricity from 0 to 165 mm under jacking stress of 1120 MPa. It was significantly less than the percentage of increasing the ultimate load capacity when the eccentricity increased from 0 to 165 mm under jacking stress of 815 MPa. Others studied the impact of using sustainable approaches and various modeling types to achieve the most beneficial outcomes [21–24]. Bedewi et al. [24] examined self-compact concrete (SCC) hollow beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars, which are lighter, less expensive, and more corrosion-resistant than steel reinforcement. Due to the inadequate elasticity of GFRP stirrups, steel stirrups had the highest shear strength, according to the maximum load. In addition, GFRP stirrups with just one connecting point exhibited the highest shear strength. Saeed and Al Amli [25] investigated the geopolymer-reinforced beam performance made of concrete from a structural perspective. Abdulrahman et al. [26] evaluated the RC beams' torsional behavior with transverse apertures reinforced by near-surface-mounted steel wire rope under repeated loads. The apertures and near-surface mounted (NSM) beams were examined. Their experiment produced and tested fifteen RC beams. Nine control beams supported by NSM had circular transverse holes in different positions, whereas six had no apertures (three strengthened and three unsupported). All transverse aperture beams showed larger twist angles and lower maximum torque under repeated loads. In the beam with the aperture closest to the support (at a quarter of the clear span), continuous, repeating loads reduced ultimate torque by 43.83%. Moving the opening location further from the supports increased torque. The apertures insignificantly impacted torque in reinforced beams. Kyprianou et al. [27] used a finite element model to investigate coated cold-formed steel beam-columns. The numerical models established cross-sectional and worldwide geometric defects for steel and sheathing geometrical and material nonlinearities. Sheathing cold-formed steel members could improve structural performance, and the separation between connections influenced member response. Wu et al. [28] proposed and implemented a wall stud-to-steel beam sleeve connection. The steel beam connection was fastened using standard bolts. Common steel angles were used for comparison. These stud-to-beam connections were tested using moment-rotation techniques. Two stud lengths were made to investigate connection performance under shear force and moment-dominant loading. The research examined component rotational stiffness, capacity, moment-rotation response, and shear-rotation response. The bonded sleeve connection was described as rigid and having partial strength since it surpassed the others [29- 31].

2. EXPERIMENTAL WORK

2.1. Specimen's Descriptions and Designation.

The research's variables mostly focused on the level's layout and the presence of the exterior strand's eccentricity, i.e., the exterior strand's eccentricity (e). Seven simply supported steel beams were constructed and tested to demonstrate the exterior strand's eccentricity impact on the steel beams' behavior during the yielding stage. The cross-sectional area was (3268 mm^2), and clear span lengths of the steel beams of (2.85 m) were identical, and the ends of the steel plate were (25×125×250) mm. Two (12.7mm) diameter pre-stresses strands were used to strengthen the sample. Table 1 and Fig. 1 show the details of the tested beams.

2.2. Fabrications and Material Characteristics

2.2.1. Type of Steel Section

Hot-rolled steel section H248x124 with a mass per meter of 25.7kg for SS400, as required by JISG 3101 [7-9], was used in the present research. The size and thickness of the steel beams are shown in Table 2.

2.2.2. Sample Fabrication and Plate Test

To ensure the wedge anchor is fixed, end steel plates were welded using E7018 electrodes to H248x124. While it can be troublesome if the structural part is not strong enough, the end steel plate may also require local stiffeners to avoid potential local yielding. Reduced stresses surrounding the holes were achieved by having the end steel plate perpendicular to the eccentricity of the external strand. [10,11]. Test samples were created in Baghdad, Iraq's National Centre for Constriction Laboratories and Research (NCCLR), as shown in Fig. 2. The relationships between stress and strain for the three samples are shown in Fig. 3. Table 3 displays the findings of the tests conducted on the samples.

Table 1 Tested Beams Details Description.

Beams No.	Serial Symbols	Profile of Strand	Eccentricity of strands(e),(mm)		
			e1*	e2**	e3***
Ref.	R	----	----	----	----
[1]	RS 000	Straight with e1e2e3 (000)	0	0	0
[2]	RS 101	Draped with e1e2e3 (101)	96	0	19.514
[3]	RS 112	Draped with e1e2e3 (112)	96	20	35.45
[4]	RS123	Straight with e1e2e3 (123)	96	96	96
[5]	RS 234	Straight with e1e2e3 (234)	165	165	165
[6]	RS 105	Sinewave profile with e1e2e3 (105)	96	0	-39

Where the eccentricity is divided into three locations at e1*= Middle span, e2**= End span, and e3***= at shear zone.

Table 2 Size and Thickness of H-section Steel [10].

Size mm	Thickness mm		Radius of curvature mm	Cross sectional area cm²	Mass per metre kg/m	Moment of inertia cm²		Radius of gyration cm		Modulus of section Cm³	
H × B	t_1	t_2	r	a		I_x	I_y	i_x	I_y	Z_x	Z_y
248 × 124	5	8	12	32.68	25.7	3540	255	10.4	2.79	285	41.1

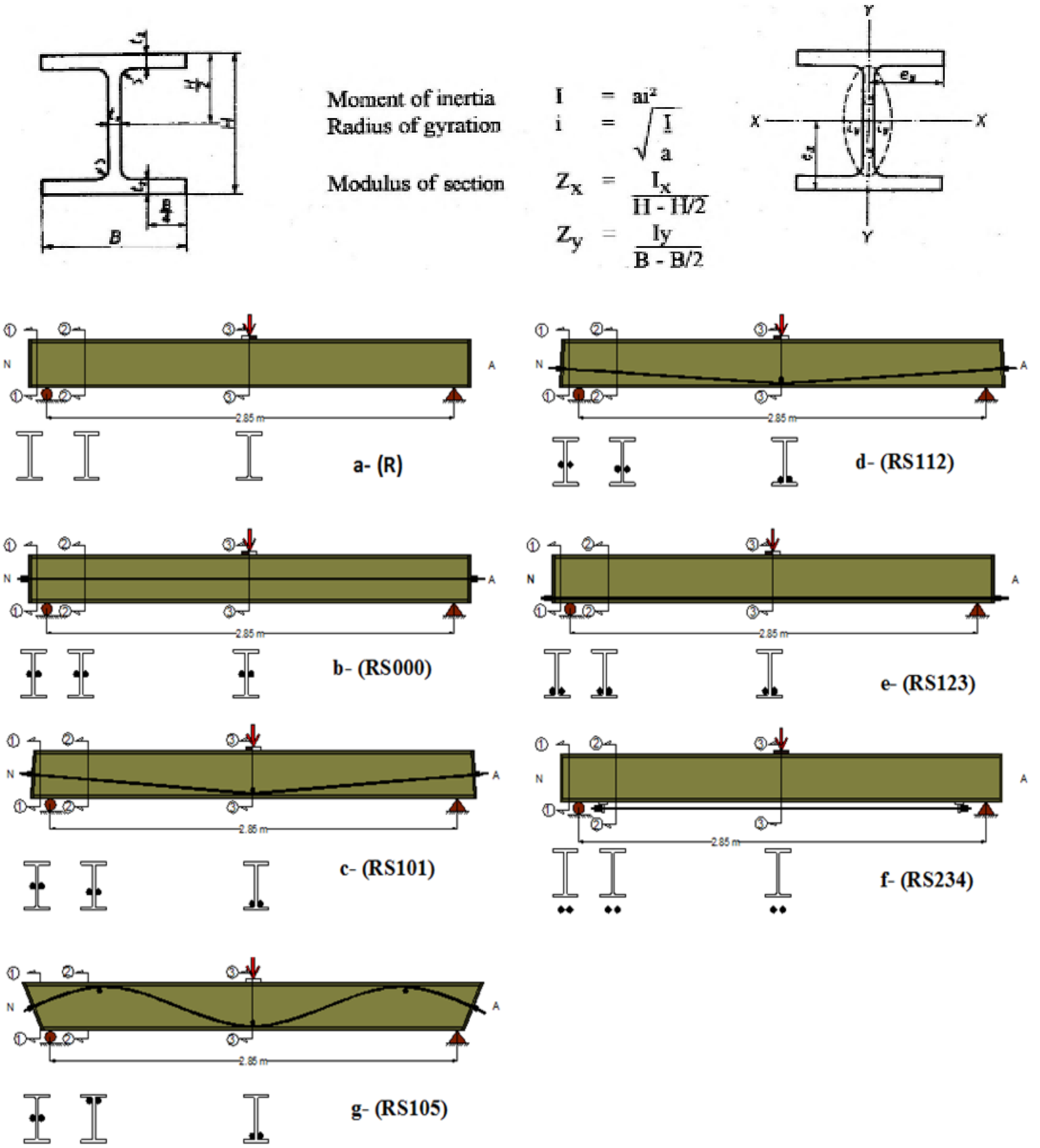

Fig. 1 Steel Beam Specifications.

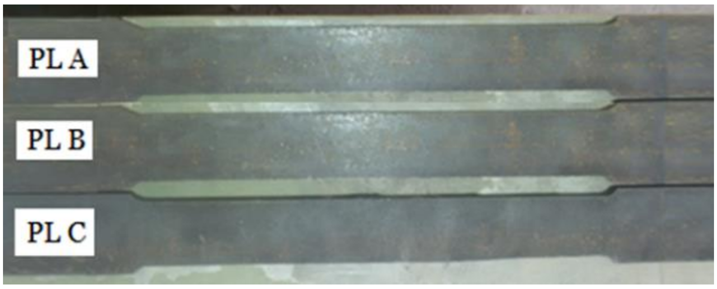

Fig. 2 The Three Steel Bone Plate.

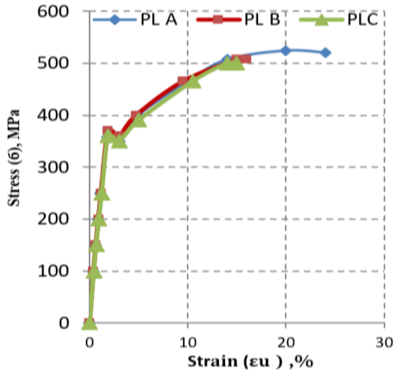

Fig. 3 Steel Coupons' Stress-Strain Curve.

Table 3 Symbols' Steel Characteristics According to the Tensile Test Performed in the (NCCLR).

Standard Requirements	Symbols No.	Yielding Stress (Fy) MPa	Tensile Stress (fu), MPa	Max. Elongation,%
Testing Results	PL A	369	507	20.5
	PL B	360	507	19.6
	PL C	356	524	20.4
	Mean value	362	513	20.17
A36/ A36 American ASTM [12]		250≤	400≤	20 ≤
Japan of JISG 3101 [7]*		245≤	400≤	17 ≤

*: Japanese material standard for hot Rolled steel plates or Japanese material standard specifications for steel plates.

2.2.3.Prestressed Strand

For the prestressed strand test Low relaxation seven-wire steel strands with a diameter of 12.7 mm and a Grade (1860) were chosen in this research, and it was confirmed in the NCCLR following ASTM A416/A416M-12a [13]. Fig. 4 displays the strand's results. To apply jacking stress across the longitudinal axis of steel beams, two low relaxation seven-wire steel strands of diameter (12.7 mm) and grade (270) were used. They were installed at various eccentricity positions ranging from (0 to 165) mm. (200) bar was utilized as the jacking stress level, and it was then transformed to (815 MPa). The prestressing stresses convert from (200 bar) to (815 MPa) as listed below:

1bar = 1.01975 kgf/cm ^{2}

The specific of gravity (g) = 9.80665 m/s^2

Then the converter factor will be =1.01975×9.80665=10

Jacking prestressing stress= 200×10= 2000 N/cm^2

The single pull jacking ram area of = 40.20 cm^2.

Jacking force = jacking stress x area of single pull jacking = 2000×40.2

Jack force =80400 N

Jacking prestressing stress = Jack force/strand area= 80400/98.7 ≅ 815 MPa

Fig. 5 depicts the hydraulic device employed.

2.3.Steel Sample Strain Monitoring

Four strain gauges positioned in the middle of the tested beams' span allowed researchers to monitor the experimental strain results for steel beams. The top and bottom of two strain gauges were set to the flanges' sector widths, and the top and bottom of the other two gauges were set to the web's clear length. Fig. 6 shows the locations of Tokyo Measuring Instruments Lab (TML) sticks.

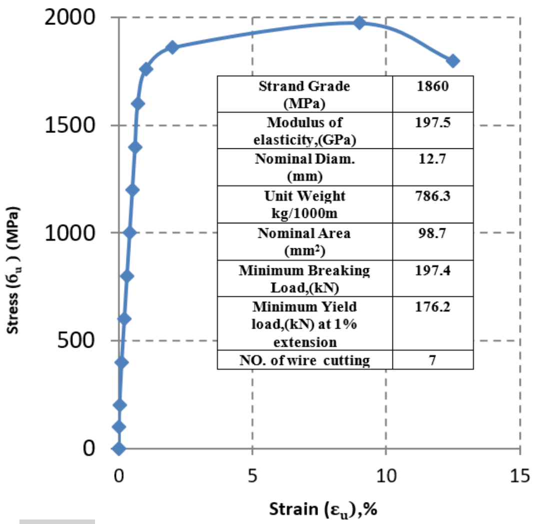

Fig. 4 Stress-Strain Curve of a Prestressed Strand.

Fig. 5 Prestressing Hydraulic Machines.

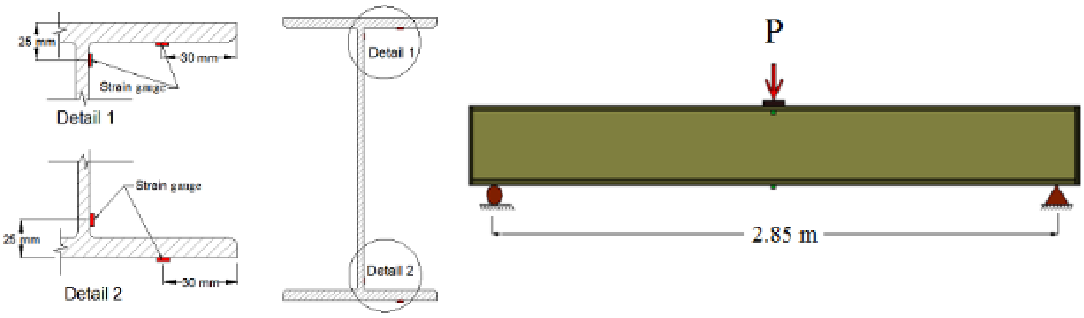

Fig. 6 Locations of Strain Gauges.

Fig. 7 Location of Double Angle (2L25x25x4).

2.4. Utilizing Saddle Points of Deviation to Ensure the Fixity of External Prestressing Strands (Deviators)

For a steel structure, saddle points or deviators are any steel plate or small steel section segments connected to the structural members by bolts or welds to provide the proper profile of the external prestressing strand according to the applied loads and the bending moment diagrams. In the present research, deviators made of a double angle (2L25×25×4) mm section were welded to the web of a steel beam at a distance of 250 mm center to center, as shown in Fig. 7. The double angle was then perforated with a hole slightly larger than the prestressing strand diameter, then the external prestressing strands were clamped using wire rope clips, also known as U-bolt clips. A U-bolt with a 16 mm diameter and a saddle secured by two 19 mm nuts were welded onto a 2L25×25×4 to make the wire rope clips fit. After the external strand was fed through the holes, anchorage steel plate and deviators were added as the final step. Both strands were subjected to stress at the same time, coming from one end. The prestressing force in the strands was carefully adjusted to avoid biaxial bending of the specimens. The U-bolt was then used; making that U-section in contact with the strands. A right-hand helix is typically included with the saddle. Finally, a torque wrench was employed to tighten the nuts to a predetermined torque. To function properly, wire rope clips must be fixed appropriately around the strand profiles used in the tested beam. Fig. 8 depicts the manufacturing process.

Fig. 8 Fabrication Procedures.

3.RESULTS AND DISCUSSION

To study the behavior of steel beams strengthened with strands at various forms of the strands' fixity profile, seven steel beams were constructed and tested under concentrated load with a simply supported beam. The tested beams had the same strands (2ϕ12.7 mm) of strengthening, clear span (2850 mm), and gross section area (3268 mm²). Based on whether the exterior strand's eccentricity is present. One steel beam serves as the reference. The other beams, which discuss steel beams strengthened by external strands, were made up of six steel beams that have been further split according to the eccentricity placement of the strand with jacking stress (fpj = 815 MPa). Table 4 shows the tested beams' results.

3.1.Load-Strain Response

According to the results, the load-strain response for the tested beams was roughly linear up until yielding, after which it behaved nonlinearly until failure occurred (buckling failure in the web and flange under the concentrated load). The load-strain curves for strengthened beams were stiffer and had higher load resistance than the reference, and the amount of stiffening increased with the eccentricity at mid-span. Additionally, it could be noted that, compared to the reference, the percentage of stiffening for tested beams with fixity decreased as eccentricity increased at the mid-span point because the fixing process tried to convert the external load produced by the prestressed strand to an internal force acting on the steel beams, decreasing the strengthening beams ductility [14-16], as shown in Fig. 9.

3.2.Ultimate and Yielding Load

Different fixity profiles were applied, and the eccentricity was changed from (0 to 165) mm at jacking stress of (fpj=815 MPa) to investigate the eccentricity location effect on the ultimate and yielding load of the steel beams. After finishing the test, it was discovered that the proportional rise in ultimate load capacity for steel beams with fixity strands rose by approximately (6.09%, 31.65%, 38.43%, 29.39%, 57.57%, and 80.17%) compared to the reference and the yielding load to eccentricity location for beams with fixity strands increased by about (-1.07%, 14.09%, 15.25%, and 39.333%). Also, the yielding load to ultimate load ratio (Py/Pu) for the strengthened beam was decreased by about (-6.74%, -13.34%, -16.75%, -11.57%, -15.27%, and -15.26%) compared to the reference, as listed in Table 5. Figs. (10) to (12) indicate the increase in the ultimate and yielding loads and the yielding load to ultimate load ratio (Py/Pu), respectively, and the percentage increase in each one of them. It can be observed that as the locations' eccentricity increased, the proportion of the yielding load increased [17,18].

Table 4 Summary of Findings from Experimental Load Tests on Steel Beams in the Yielding Stage.

Beams No.	Series Symbols	Ultimate Load (Pu),(kN)	Yielding Load, (Py) (kN)	Mid-Span Experimental Strain at Yielding Stages (εy. ×10-6)			
				Top Flange	Bottom Flange	Top	Top Flange
Ref.	R	287.5	191.67	-1357	1810	-935	1539
[1]	RS 000	305	189.63	-1272	1108	-1810	755
[2]	RS 101	378.5	218.68	-1810	1277	-1119	977
[3]	RS 112	398	220.90	-1810	1335	-1242	697
[4]	RS123	372	210.13	-1810	1368	-1279	1101
[5]	RS 234	518	292.66	-1481	1235	-1810	880
[6]	RS 105	453	267.06	-1389	1328	-1810	981

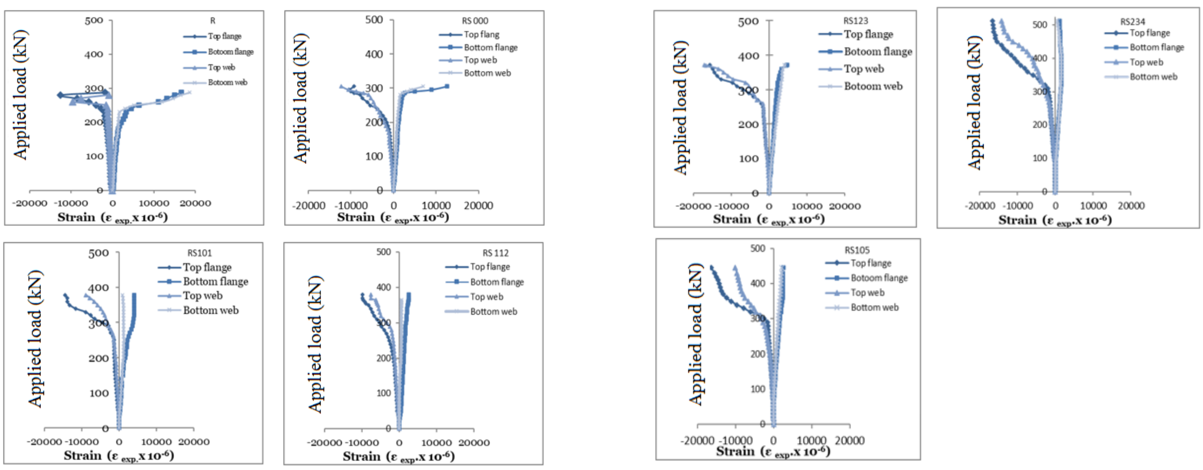

Fig. 9 Relationship of Applied Load-Versus Strain for the Tested Beams.

Table 5 Ultimate and Yielding Loads of the Test Specimens as Determined by the Experiment.

Beams No.	Series Symbols	Ultimate load,(Pu) (kN)	Percentage of increased ultimate load (Pu), (kN) relative to reference beam, (%)	Yielding load, (Py), (kN.)	Percentage of increased yielding load (Py), (kN) relative to reference beam, (%)	Yielding load to ultimate load ratio $(\frac{Py}{Pu})$	Percentage of increased $(\frac{Py}{Pu})$ ratio relative to reference beam, (%)
Ref.	R	287.5	------	191.67	------	66.67	------
[1]	RS 000	305	6.09	189.63	-1.07	62.17	-6.74
[2]	RS 101	378.5	31.65	218.68	14.09	57.78	-13.34
[3]	RS 112	398	38.43	220.90	15.25	55.50	-16.75
[4]	RS123	372	29.39	210.13	9.63	56.49	-15.27
[5]	RS 234	518	80.17	292.66	52.68	56.50	-15.26
[6]	RS 105	453	57.57	267.06	39.33	58.95	-11.57

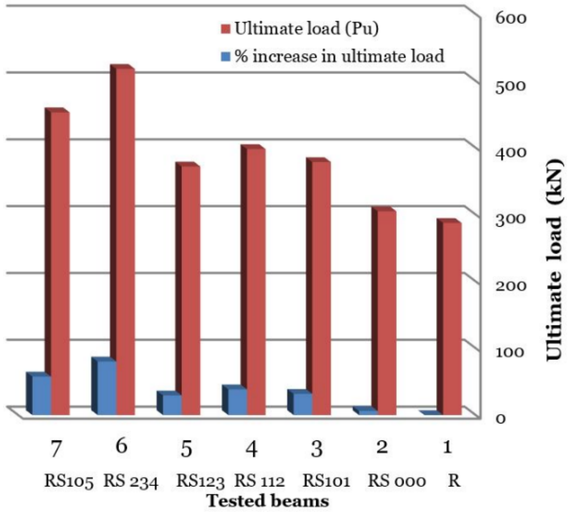

Fig. 10 The Ultimate Load and the Ultimate Load % Increase of the Tested Beams.

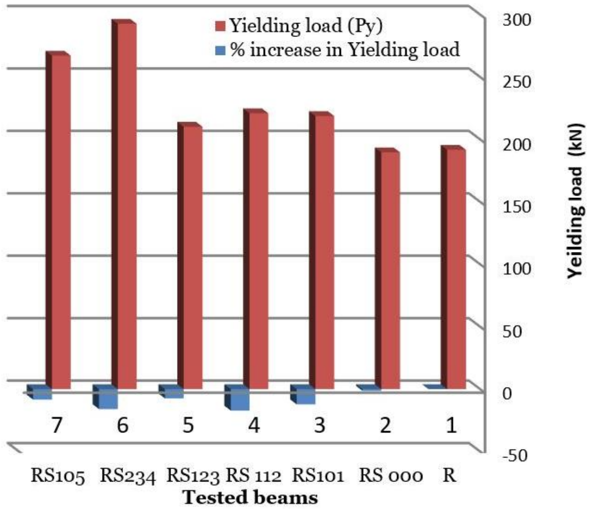

Fig. 11 The Yielding Load and the Yielding Load % Increase of the Tested Beams.

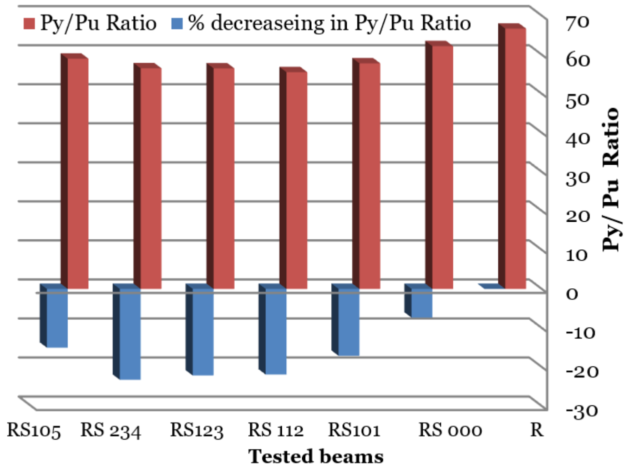

Fig. 12 The Yielding to Ultimate Load Ratio and Yielding Load to Ultimate Load Ratio % Increase of the Tested Beams.

3.3.Effect of Eccentricity Location

To investigate the effect of eccentricity location on the yielding strain of the steel beams, several fixity profile approaches were used, and the eccentricity was varied from (0 to 165) mm at jacking stress (fpj=815 MPa). An externally prestressed strand improved the bottom and top flange and increased the web resistance under applied load. On the other hand, the positions of yielding strain for the tested beams shifted from the bottom flange to the top region compared to the reference beam [18, 19], as listed in Table 6. For strain in the top flange, compared to the reference beam, it was found that the percentage of increase in strain growing for beams with fixity strands increased by roughly (-6.26%, 33.39%, 33.39%, 2.36%, 33.39%, and 9.14%) for each beam with eccentricity location increased from (0 to 165) mm. The negative sign in beams with fixity strand at eccentricity (000) is due to decreasing in top flange strain as a result of improving the web resistance and decreasing the clear distance between two flanges. When the eccentricity position was increased from 0 to 165 mm, the percentage increase in strain in the bottom flange for the beams with fixity strands dropped by around (38.78%, 29.45%, 26.24%, 24.42%, 26.63%, and 31.77%) compared to the reference beam. When the eccentricity position was adjusted from 0 to 165 mm, the top web strain for beams with fixity strands increased by roughly 93.28%, 19.68%, 32.83%, 93.58%, 36.79%, and 39.58%, respectively, compared to the reference beam. Finally, compared to the reference beams, the percentage rise in the bottom web for beams with fixity strand dropped by around (50.94%, 36.51%, 54.71%, 28.47%, 36.26%, and 36.26%). For the top and bottom regions of the tested beams, the yielding strain and percentage increase in the yielding stage strain are depicted in Figs. (13) to (15), respectively.

Table 6 Results from Experiments Showing an Increase in the Yielding Strain of Tested Beams in the Strain Middle of the Span at the Yielding Stage.

Series Symbols	Experiments with Strain and Percentage Increases in Strain at Mid-Span Positions During the Yielding Stages								First Buckling Segment Part Location
	Top Flange (εy) × 10-6	Top Flange Percentage Increasing, %	Bottom Flange (εy) × 10-6	Bottom Flange Percentage Increasing, %	Top of web(εy) ×10-6	Top web Percentage Increasing	Bottom of Web (εy) ×10 -6	Top Web Percentage Increasing, %	
R	-1357	0	1810	0	-935	0	1539	0	Bottom flange
RS 000	-1272	-6.26	1108	-38.78	-1810	93.58	755	-50.94	Top web
RS 101	-1810	33.34	1277	-29.45	-1119	19.68	977	-36.51	Top flange
RS 112	-1810	33.39	1335	-26.24	-1242	32.83	697	-54.71	Top flange
RS123	-1810	33.39	1368	-24.42	-1279	36.79	1101	-28.47	Top flange
RS 234	-1481	9.14	1235	-31.77	-1810	93.58	880	-39.77	Top web
RS 105	-1389	2.36	1328	-26.630	-1810	93.58	981	-36.26	Top web

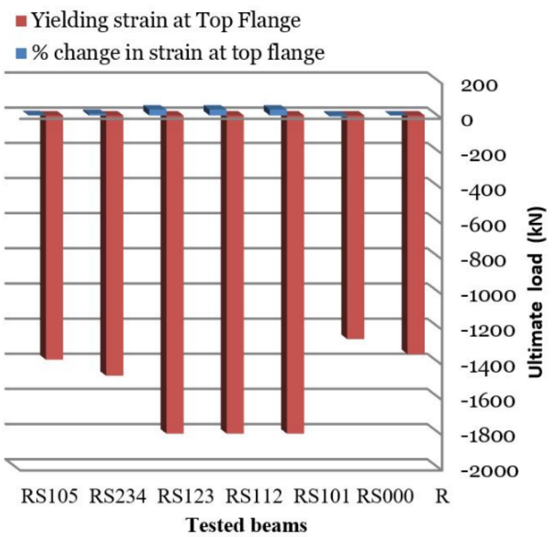

Fig. 13 Yielding Strain and Yielding Strain Increasing Percentages of Tested Beams at Various Eccentricity Values.

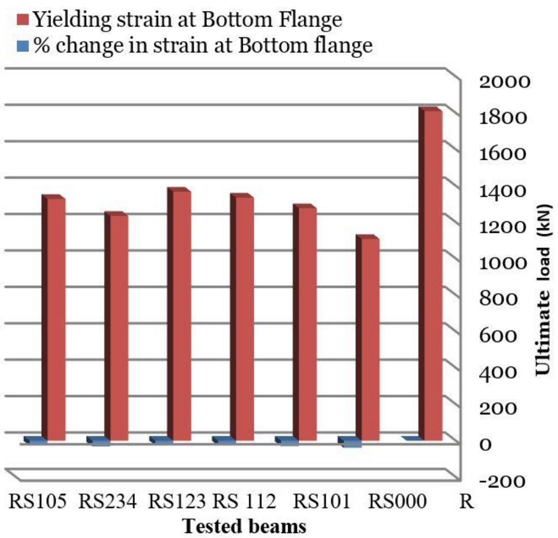

Fig. 14 Yielding Strain and Yielding Strain Increasing Percentages of Tested Beams at Various Eccentricity.

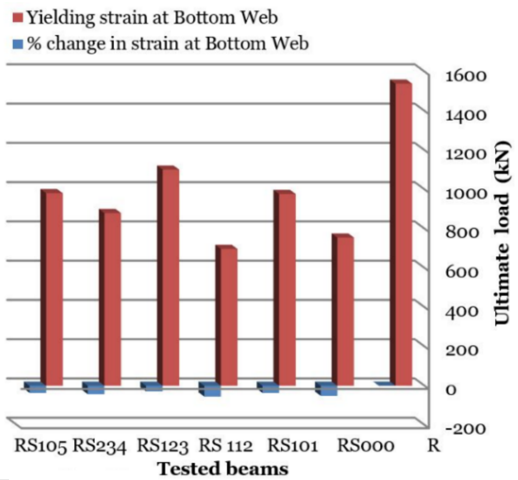

Fig. 15 Yielding Strain and Yielding Strain Increasing Percentages of Tested Beams at Various Eccentricity Values.

4.CONCLUSION

The experimental results of steel beams that the exterior strand's eccentricity strengthened at the yielding stage led to the following conclusions.

1) As strand eccentricity increased under applied jacking stress, the ultimate load of tested strengthened beams increased. The increase in the maximum load of the strengthened tested beams above the reference was 80.17%.
2) The yielding loads of strengthened tested beams increased with increasing strand eccentricity. In the RS234 sample, the maximum yielding load of reinforced tested beams had risen by 52.68% above the reference when the eccentricity increased from zero to 165 mm.
3) Compared to the reference beam, the yielding strain positions for all tested beams shifted from the bottom to the top region.
4) As strand eccentricity increased, the amount of strain added to the top flange of tested strengthened beams during the yielding stage increased in percentage. In the RS000, RS112, and RS234 samples, the most significant percentage of strain increase above the reference was 33.38% in the top flange of strengthened beams examined.
5) As strand eccentricity increased, the proportion of strain increase at the bottom flange reduced as the strengthened tested beams progressed through the yielding stage. The most considerable percentage reduction in strain measured in the bottom flanges of strengthened beams was 38.79% compared to the reference beam using the RS000 sample.
6) As strand eccentricity increased at jacking stress, the tested strengthened beams' top web strain increased significantly during the yielding stage. The top web of strengthened tested beams experienced the highest percentage of strain increase (93.59%) in the RS000, RS234, and RS105 samples compared to the reference.
7) The percentage increase in bottom web strain during the yielding stage for the strengthened beams tested reduced as strand eccentricity increased. Compared to the reference beam, the RS234 sample resulted in a maximum reduction of 39.77% in bottom web strain for reinforced tested beams.

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