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Torsional Behavior of Reinforced Concrete Beams Repaired or Strengthened with Transversal External Post – Tension Elements

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Abstract

This paper investigate the efficiency of using post-tension stainless steel links and steel links systems for strengthening and repairing R.C beams without and with web opening subjected to pure torsion. Post-tension force was produced in vertical links of high strength material using steel plate at top and bottom surface of the beams anchored with fine threads. Twenty Two specimens are divided into two parts, one part deal with solid beams and other deal with beams with web opening. The effect of post-tension force in vertical links, spacing between vertical links, post-tension technique (links – U shape), plates configuration and opening length are the effective variables on the torsion capacity were studied in this research. The experimental results shows that the post-tension system is very effective strengthening and repairing method to enhance torsion beam capacity up to 27.55 %. This system also increase the beams ductility, delay the appearance of first crack and reduce the crack width within increasing in applied torque till failure. Torsion capacity of beams with web opening strengthened with post-tension system significantly improves over the control beams and in some case reach the capacity of solid control beam. Failure of beams strengthened with post-tension system was due to spalling of concrete cover due to torsional moment. The failure of beams with web opening strengthening with post-tension system was in solid part not in opening corner as control beams with web opening.

Keywords: Torsion, Post-Tension, Strengthening, Ductility, Web Opening

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I. INTRODUCTION

Modern civilization relies upon the continuing performance of its civil engineering infrastructure ranging from industrial buildings to power stations and bridges. For the satisfactory performance of the existing structural system, the need for maintenance and strengthening is inevitable.

During its whole life span, nearly all engineering structures buildings faces degradation or deteriorations. The main causes for those deteriorations are environmental effects including corrosion of steel, gradual loss of strength with ageing, variation in temperature, freeze-thaw cycles, repeated high intensity loading, contact with chemicals and saline water and exposure to ultra-violet radiations. Addition to these environmental effects earthquakes is also a major cause of deterioration of any structure. This problem needs development of successful structural retrofit technologies. So it is very important to have a check upon the continuing performance of the civil engineering infrastructures. The structural retrofit problem has two options, repair/retrofit or demolition/reconstructions. Previously, the retrofitting of reinforced concrete structures, such as columns, beams another structural elements, was done by removing and replacing the low quality or damaged concrete or/and steel reinforcements with new and stronger material and new techniques.

In recent decades, Transverse opening in reinforced concrete beams has become one of civil engineering challenges. Especially, in high-rise buildings in where the height of the floor is not sufficient to place their utility under the soffit of the beam. Transverse opening in reinforced concrete beams are often provided for the passage of utility ducts and pipes. Ducts are necessary in order to accommodate essential service such as water supply, electricity, and telephone and computer network especially in the construction of multistory buildings. However providing an opening in the beams cause cracks around the opening thus reduce the beam stiffness which lead to the need of strengthening for beams.

Recently, strengthening of reinforced concrete (RC) beams subjected to torsion is receiving increased attention. Torsion is considered one of the main factors affecting the stability of structural elements. Structural elements subjected to torsion experience diagonal tension and compression and fails in a brittle manner which may result in a progressive collapse of the building.

One of the new techniques widely used in strengthening and repair is external post - tension elements. External post – tension techniques is one of the widely used as strengthening technique owing to its advantages such as: economical construction, easy and speed of installation and maintenance, easy bolts anchor placement , enabling finishing after strengthening and in case of bridge, minimal disruption to traffic flow.

Most researches have been focuses of shear strengthening using post tension system. Sayan and nathavudh was studied the strengthening of RC beams by transverse external post-tension under shear force (2010) [3]. Miguel and Aurelia was studied strengthening of flat slabs against punching shear using post-installed shear reinforcement (2010) [4]. El-shafiey and Atta, (2012) studying the retrofitting of reinforced concrete beams in shear using external prestressing force [5]. Most researches of torsional strengthening or repairing was done using composite material. Khaled, (2008) was studying the torsional behavior of RC beams strengthened with fiber reinforced polymer sheets [6]. Fawzy, Mahmoud (2014) was studying performance of RC beams with web opening subjected to pure torsion strengthened with CFRP [7]. Emad and Atta (2015) was studying torsional strengthening of RC box beams using external prestressing technique [8]. The motivation to prepare this study was a lack of information in world codes about how to design beams subjected to pure torsion strengthening with post-tension links in the vertical direction.

II. RESEARCH SIGNIFICANCE

Many existing elements of buildings in factories and bridges subjected to torsion need to strength or repair. This research was focus on the most parameters effecting on using the post-tension technique to enhance torsional moment capacity of exhibited R.C beams. However, limited information is available in the literature on the viability of using post-tension technique to strengthen or repair R.C. beams. So, this study is attempting to fill the gap in the literature.

III. EXPERIMENTAL PROGRAM

A. *Specimens Details*

To study the variables effecting on the behavior of reinforced concrete beams without and with web opening strengthened or repaired with external post – tension elements in the transverse direction, a Twenty Two full-scale specimens were constructed for this objectives. A T- shaped reinforced concrete beams with cross-section (bw/D/bf/df) equal (200/400/400/100 mm) with a total length of 1700 mm was chosen for all tested reinforced concrete specimens. The specimen has a "Z" shape with right angles at both joints. The middle part of the specimen 1300 mm is the testing-strengthening or repaired zone, which was subjected to pure torsional moment during loading. The two cantilever parts 400 mm in length, were designed to withstand the maximum bending moment and shear force which could occurs during testing. The beam section was designed according to the Egyptian code, ECP 203-2007. All the tested specimens were reinforced with two 12 mm diameter longitudinal bars in both bottom and top flanges. Diameter of 10 mm stirrups spaced by 175 mm was used throughout the beam span. Fig.1- (a) and fig.1- (b), showed overall layout of tested beams (plan, elevation and section) with full dimensions and reinforcement arrangement and details for stirrups and arrangement of heavily reinforcement parts and positions of loads.

All tested beams were identified based on the following naming system. The first character of beam code is R (Rectangular), T (T – Section) indicates the cross – section type. The second character indicates the condition of beam (S: beam without web opening, O: Beam with web opening). Third character indicates the material of vertical links used in the strengthening or repair (S: Strengthening with links of high grade steel, A: Strengthening with links of stainless steel). Fourth character indicates the strengthening technique (L: Links, U: U shape stirrups). The beam number was followed the beam code. Example (TSAL-1) indicates the beam number 1 is with T cross-section strengthening with post-tension stainless steel links.

B. *Materials properties*

All tested specimens were cast with normal-strength concrete mix of local material that has high workability and strength requirement of the standard specification. Clean of ordinary siliceous sand with Fineness modulus was 2.75, crushed hard Dolomite with maximum grade size of 25 mm , ordinary Portland cement of 42.5N grade and Clean drinking fresh water free from impurities were used for mixing and curing the tested beams. Normal mild steel bars with yield strength and ultimate strength were 310 MPa and 480 MPa, respectively was used as stirrups. High tensile steel bars with yield strength and ultimate strength were 369 MPa and 598 MPa, respectively were used for all other reinforcement. External steel links and stainless steel links were used in the strengthening and repairing. Steel links were locally fabricated using high-grade steel bars of 10mm. Stainless steel links were locally fabricated using high-grade stainless steel bars of 12 mm which has yield strength and ultimate strength were 650 MPa and 800 MPa, respectively. The concrete mixes proportions, and compressive strength at 28 days are presented in Table 1.

C. *Test Setup and instrumentation*

The test set-up used in this study consisted of rigid steel frames supported by the laboratory rigid floor in Reinforced Concrete laboratory at faculty of engineering-Benha University. All the beams were tested under pure torsion. Schematic arrangement of loading for the tested beams is shown in fig. (5). the torsion was applied to test specimen using of the cantilevers parts, using rigid steel beam and hydraulic jack at the center of steel beam. Two hinged supports were used at both ends of the Z-shape, which were capable to incline in the vertical plane to translate the pure torsional moment from both cantilever parts to the test specimen. All specimens were centered from both sides and then the supports were centered. The two centers were placed on each other (centers of beam and support). These steps were repeated between tested beams and hydraulic jack to be sure of producing pure torsion.

The load was applied using a hydraulic jack of 800 KN capacity and measured by using a proving ring of 100 KN capacity. The applied load was equally distributed on both cantilevers by rigid steel beam.

The twisting angles of specimens during test were determined by measuring deflections under the both loaded points through linear variable differential transducers (LVDT) of 56 mm displacement capacity and 0.001 mm accuracy, then, it was divided by spacing apart (equal 250 mm) to get the twisting angle per unit length. The strain of external post-tension links were measured through electrical strain gauge with measuring arm of 1 µm accuracy.

D. *Strengthening and Repairing Technique*

This research puts spotlight on the torsional behavior of R.C beams without and with web opening repaired or strengthened with transversal external post–tension elements. In this study steel links of 10 mm diameter and stainless-steel links of 12 mm are used in vertical direction. Steel plates of 30 mm is used on the top and bottom surface of beams. Links in the transverse direction was anchored with steel plates by threads. Because of the short – length required, the post – tension force can most easily be provided using high strength bars with the required Prestress produced using fine threads.

Details of control beams are presented in table (2), details of solid beams strengthened or repaired with post-tension system are presented in table (3) and details of beams with web opening strengthened or repaired with post-tension system are presented in table (4).

The variables focuses in the research are as follows:

1) Material of post - tension elements (high-grade steel – stainless steel).
2) Technique of post - tension elements (links- stirrups U shape).
3) Spacing between post - tension elements (S= 300 mm and S= 400 mm).
4) Position of strengthening part of test zone (middle – overall length).
5) Bearing Plate size (plate configuration).
6) Web opening length (bo).
7) Number of cut-off internal stirrups.

IV. EXPERIMENTAL RESULTS & DISCUSSION

This section presents and discuss the experimental results of all the tested reinforced concrete beams. Test results was discussed into two parts, the first part was discussed the results of solid beams and the second part was discussed the results of beams with web opening.

The test results include cracking torsional moment, ultimate torsional moment, torsion-twisting angle relationship, strain of external links and crack pattern under increment of loading.

Part I, Experimental results and discussion of solid beams as follow:

In this part, the behavior of thirteen reinforced concrete solid T –beams subjected to pure torsion was presented and discussed.

Tested specimens are sorted in seven groups named A, B, C, D, E, F and G. Group A which consist of specimens (RS) and (TS-1) as a control specimens. Group B which consist of specimens (TS-1), (TSSL-1), (TSSL-2), (TSAL-1) and (TSAL-2) to study the effect of post-tension force in external links and links materials. Group C which consist of specimens (TS-1), (TSSL-3), (TSSL-4), (TSAL-3) and (TSAL-4) to study effect of spacing between links. Group D which consist of specimens (TS-1), (TSSL-1) and (TSSU-6) to study the effect of strengthening technique (links – U-shaped). Group E which consist of specimens (TS-1), (TSSL-1), (TSSL-3), (TSAL-1) and (TSAL-3) to study the effect of strengthening zone (at mid span – overall span). Group F which consist of specimens (TS-1), (TSSL-3), (TSSL-5), (TSAL-3) and (TSAL-5) to study the plate size (4 plates- 8 plates). Group G which consist of specimens (TS-1) and (TSAL-6) to study effect of using this technique in repairing. All specimens details are shown in fig (4).

The experimental results, as shown in table (5) were presented and discussed as follow:

A. *Cracking and Ultimate Torsional Moment*

1) *Effect of post-tension links force*

Strengthening using external post – tension stainless steel links and steel links has an effect on the solid beams torsion capacity. Increasing of post-tension force in this research was applied by increasing strain in vertical links with double value, so the post-tension force become twice and increase strength of links material (steel-stainless steel). Cracking torsional moment of strengthening beams (TSAL-1), (TSAL-2), (TSSL-1) and (TSSL-2) were increased by 36.93 %, 30.77 %, 28.85 % and 15.38 % with respect to the control beams (TS-1). Ultimate torsional moment of strengthening beams (TSAL-1), (TSAL-2), (TSSL-1) and (TSSL-2) is 26.80 %, 19.53 %, 15.96 % and 9.33 % with respect to the control beams with (TS-1), respectively. From the experimental results, one can notice that increasing the post tension force in links improves the cracking and ultimate torsional moment due to increase bearing stress under steel plates that lead to more confinement of tested specimens.

The strengthening using EPT links increase the beam stiffness and reducing the twisting angle as shown in Fig. (7) and fig. (8). The twisting angle values at the ultimate load of control beams of strengthening beams (TSAL-1), (TSAL-2), (TSSL-1) and (TSSL-

2) is reduced by 448.00 %, 328 %, 243.6 % and 193.25 % when compared to control beam (TS-1). As we increase the post tension force, higher ductility of strengthened beams was noticed and the rotation of beam reduced with efficient value.

2) Effect of strengthening zone of beams

Cracking and ultimate torsional moments of beams strengthened with links at overall test zone increased more than beams strengthened at mid span. Using vertical post-tension links for strengthening at overall the test zone of the beams (TSAL-1) and (TSSL-1) enhances the ultimate torsional moment by 22.42% and 13.74 % with respect to (TSAL-3) and (TSSL-3), respectively. Strengthening overall the test zone of beams leads to delay in the cracking which improves the cracking torsional moment up to 20.27 % and 3.11 % in case of using stainless steel links and steel links, respectively.

According to fig. (11) and fig. (12), the using of vertical post-tension links as strengthening at overall test zone can obviously effect on the ductility of beams more than strengthening beams at mid span by 407.93 % and 134.80 % in case of using stainless steel links and steel links, respectively. The reason was the restraint due to post-tension force in links. The rotation of strengthening beam at mid span was higher because the plates of strengthening placed at mid span divided the span into two parts.

3) Effect of spacing between links

Different spacing between vertical links were used to strengthen the tested R.C beams subjected to pure torsion. Test results indicates that as the spacing between the vertical links increase, the ultimate torsional moment decrease. As the spacing change from (300 mm) (11.81 in) to (400 mm) (15.74 in) that leads to reduction in ultimate torsional moment by 2.72 % and 1.96 % in case of using stainless steel links and steel links, respectively. That also leads to increase in cracking torsional moment by 8.08 % and 3.70 % in case of using stainless steel links and steel links, respectively. Increasing of strengthening zone length by increasing the spacing between links leads to delay of cracking occurs.

Increasing the spacing between the vertical links make the beams low stiff and decrease its ductility. The twisting angle values at same torsional moment have obviously decreased when the spacing between links increase, as shown in fig. (9) and fig. (10).

4) Effect of torsion strengthening with different steel plate configuration

In this research, two steel plates size was used for strengthening tested specimens at the same level of post-tension force in the external links. Increase the plate size lead to increase in cracking and ultimate torsional moment of tested specimens however this reducing the bearing stress under steel plates. The prediction reason of this is the restraint of beams against deflection under applied torque produced from increasing the plate size. The experimental test results reveal that increase the plate size when strengthening beams with stainless steel links, increase the ultimate torsional moment by 4.09 %.

Increasing plate size also effect on the twisting angle of tested beams. As the plate size increase, the twisting angle at the same value of applied torque decreases by 32.40 as shown in fig (13).

5) Effect of strengthening techniques (links – U shape)

In this section, steel used in strengthening of tested beams only because the stainless steel cannot deformed as U shape. The use of U shape stirrups with steel plates at the top surface of the beam anchored with fine threads is more effective to improve the torsional capacity. The U shape technique increase the ultimate torsional moment by 5.85 % and reach the capacity of beams strengthened with stainless steel links.

Fig. (15) Shows that the Using U shape technique make the beam stiff and decrease the twisting angle by 45 % at the same applied torque.

6) Effect of using post-tension stainless steel links in the vertical direction as a repairing technique

One beam was loaded till the first crack occurs then strengthened with external post-tension stainless steel links. Test results shows that using this technique in the repairing process has an effect on the torsional capacity. Repairing using this technique increase the ultimate torsional moment by 16.56 % with respect to control specimen. Repairing with this technique is also effective to enhance the beam ductility and its stiffness. Fig. (14) Shows that twisting angle was decreased by 274.12 % with respect to control beams.

B. Crack pattern and mode failure of solid beams

Due to torsion, beams withstand a large number of diagonal compressive and tensile stresses. Concrete carry the compressive stresses and the internal reinforcement of stirrups and longitudinal bar carry part of the tensile stresses. The rest part of tensile stresses carry by the external post-tension system. Torsion failure can occurs by crushing of materials or separation of concrete at crack zone. For control beams and strengthened or repaired solid beams was failed due to torsion moment. When the applied torsion moment increase, diagonal cracks were propagated forming a spiral trajectory on four sides of the testing beams with angle 45.

More cracks were observed in the control beams than the strengthened beams. Control beams was failed due to separation of concrete due to compressive strength. Using post –tension links delay the cracks occurrence than control beam. Crack width was noticed smaller than control beam. Failure of strengthened beams was due to crushing of concrete. Fig. (6-a) and fig. (6-b) shows crack pattern of control and strengthened solid beams.

Part II, Experimental results and discussion of beams with web opening as follow:

A Series of three reinforced concrete beams with different web opening was tested to evaluate the effect of increase of web opening length on the torsional behavior of beams. Also, six RC beams with web opening strengthened with post-tension links in the transverse direction was tested to investigate the effect of using post-tension technique on torsional capacity.

The experimental results, as shown in table (6) were presented and discussed as follow:

A. Cracking and Ultimate Torsional Moment

1) Effect of Web opening length (bo)

The presence of web opening in beams has been investigated directly effected on the cracking torque and ultimate torque as expected. As the opening length increase, the ultimate torsional moment of (TO-1), (TO-2) and (TO-3) was decreased by 13.60 %, 34.82 % and 37.64 % with respect to solid beam (TS-1), respectively. The decreases in the ultimate torsional moment of (TO-2) and (TO-3) with respect to beam (TO-1) are 24.50 %, 27.80 % respectively. The variation in ultimate torque of beam (TO-2) and beam (TO-3) are roughly changed. The reasons of this may be referred to that after the first crack occurs, the resistance comes from the stirrups and longitudinal bars and the outer concrete skin. The number of stirrups at this zone was cut-off while constructing opening in this beam is two stirrups.

Twisting angle has noticeable effect with the presence of web opening. Fig (16) shows that the twisting angle at the same level of torsional moment for the control specimens with web opening (TO-1), (TO-2) and (TO-3) increased by 154.80 %, 352.43 % and 641.49 % respectively with respect to the control solid beam (TS-1). It can be seen that at the same torsional moment, the twist angle of beams increased by increasing the web length. This refer to as the opening length produced a weaker beam with low stiffness.

2) Effect of strengthening using post-tension system

Strengthening using external post–tension links has an effect on the beam with opening torsion capacity. Ultimate torsional moment of strengthened beams with web opening was higher than other unstrengthening beams. ultimate torsional moment of strengthening beam with web opening (TOAL-1), (TOAL-2) and (TOAL-3) is 20.63 %, 27.55 % and 21.19 % with respect to the control beams with web opening (TO-1), (TO-2) and (TO-3), respectively. ultimate torsional moment of strengthening beam with web opening (TOSL-1), (TOSL-2) and (TOSL-3) is 6.17 %, 5.07 % and 2.00 % with respect to the control beams with web opening (TO-1), (TO-2) and (TO-3), respectively. The appearance of the first cracks depends on the transverse prestressing force. Transverse prestressing force in the strengthening delay the appearance of the first crack, Thus further shear stress can be resist by concrete which is remain uncrushed. It can be also concluded that Transverse prestressing force in the strengthening zone resist shear stress after cracking with internal stirrups and delay the failure of the beams. Therefore, stainless steel links are more effective than steel in the increasing the torsional moment capacity.

Strengthening of opening at the opening zone increase the beam stiffness. At the same level of torsional moment, the twisting angle of beam (TOAL-1), (TOAL-2) and (TOAL-3) decreased by 30 %, 57.89 % and 72.92 % with respect opening control beam (TO-1), (TO-2) and (TO-3), respectively. At the same level of torsional moment, the twisting angle of beam (TOSL-1), (TOSL-2) and (TOSL-3) decreased by 8.33 %, 56.38 % and 72.11 % with respect opening control beam (TO-1), (TO-2) and (TO-3), respectively as shown in fig. (17) to fig.(22).

V. CRACK PATTERN AND MODE FAILURE OF BEAMS WITH WEB OPENING

Control solid specimens and tested beams with different opening length exhibited torsional failure mode with spiral diagonal cracks as expected. The progress of cracks provided useful information about the failure mode of tested beams. The first crack appeared at the corner of opening web, then, within increasing the cracks at the corner of the opening becomes more wider and new cracks propagated through the upper and lower chords of web opening. With increasing the loading, diagonal cracks increased forming a spiral trajectory on the four sides around the opening zone of tested specimen. The inclination of the crack was about 45° to the longitudinal axis of the beam. The failure of the tested beams with web opening took place at the middle part of the beams span, which was affected by the web opening. For specimen with web opening (TOAL-1) and (TOSL-1), the first cracks occur at the corner of opening. This cracks was has smallest wide and length within many load interval due to the presence of strengthening at opening zone. The crack pattern of this specimen was shown in fig (6-b) and fig. (6-c). It was shown that the cracks propagated with more intensity through the lower and upper chord of opening and with increasing in torsional moment, the cracks propagated outside the opening zone due to the presence of strengthening at opening zone. The position of failure was take place in the outside of the opening zone and the crack width was smaller than it is control-opening beam. It's also noticed that no spalling of the concrete cover occurs at ultimate torsional moment. For test specimen (TOAL-2), (TOAL-3), (TOSL-2) and (TOSL-3) with web opening length larger, the failure was occur at the opening zone or nearest the opening border due to the cut-off of internal stirrups. The failure also was due to spalling of concrete cover at the ultimate torsional moment. Crack width in between links zone in specimens (TOAL-3) was larger than the specimen (TOAL-2) which indicates that the crack width increase with increase the opening length.

VI. CONCLUSIONS

Based on the investigation and experimental results described, a few conclusions may be considered for strengthening and repairing using post-tension vertical links under pure torsion. The following conclusions can be summarized as follow:

1) Using post-tension links in the transverse direction as strengthening method enhances the torsional capacity of the solid tested beams and beams with web opening. The increase in ultimate torsional moment was 36 % and 20 % in case of solid and beams with opening, respectively.

2) Increasing post-tension force by increase strain of links or change strength of material improves the ultimate torsional moment and increase beam stiffness.
3) Strengthening using post-tension overall the tested zone of beams was more effective than strengthening at mid span.
4) Increasing spacing between vertical links reduce the ultimate torsional moment by 2.72 %
5) During testing of beams of all strengthened beams, vertical links don't lose out indicating that this method provides effective installation especially the effective of anchorage at both ends.
6) The increase of plate size leads to increasing ultimate torsional moment by 4.09 % and decreasing twisting angle.
7) Strengthening of beams with web opening produce the failure at the solid zone in case of beams with (bo/d=1) and increase its capacity more than solid control beam.

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TABLES & FIGURES

Table - 1
Concrete mix proportions and compressive strength

Mix No	*Mix proportions Kg/m3*				*Unit Weight*	*C. A/ F.A.*	*W/C%*	*Cube Compressive Strength At 28 days MPa*
	C	*W*	*F.A*	*C.A*				
1	*350*	*175*	*620*	*1240*	*2385*	*2*	*50*	*37.50*

Where
C= Cement
W = Water
F. A. = Fine aggregate
C. A. = Coarse aggregate

Table – 2
The Experimental Test Program of Control Beams (Solid Beams and With Web Opening Beams)

specimens	*Opening dimension*		*Notes*
	Depth (mm)	*Length bo (mm)*	
RS	----	----	
TS-1	----	----	
TO-1	*100*	*100*	*Opening at mid span*
TO-2	*100*	*200*	
TO-3	*100*	*300*	

Table – 3
The experimental test program of solid strengthening and repairing beams

specimens	*Retrofit schemes*				*Notes*
	Links number	*Plates number*	*Retrofit zones*	*Plate size B X L X T (mm)*	
TSSL-1	*8*	*8*	*overall tested zone*	*400 X 125 X 30*	*Study prestressing force*
TSSL-2	*8*	*8*	*overall tested zone*	*400 X 125 X 30*	
TSSL-3	*4*	*4*	*at mid span*	*400 X 125 X 30*	*Study effect of spacing between EPT links*
TSSL-4	*4*	*4*	*at mid span*	*400 X 125 X 30*	
TSSL-5	*4*	*2*	*overall tested zone*	*450 X 400 X 30*	*Study effect of plate size*
TSSU-6	*4*	*4*	*overall tested zone*	*400 X 125 X 30*	*Study effect of strengthening technique*
TSAL-1	*8*	*8*	*overall tested zone*	*400 X 125 X 30*	*Study prestressing force*
TSAL-2	*8*	*8*	*overall tested zone*	*400 X 125 X 30*	

TSAL-3	*4*	*4*	*at mid span*	*400 X 125 X 30*	*Study effect of spacing between EPT links*
TSAL-4	*4*	*4*	*at mid span*	*400 X 125 X 30*	
TSAL-5	*8*	*8*	*overall tested zone*	*400 X 125 X 30*	*Repaired after first crack*

Table – 4

The experimental test program of strengthening and repairing beams with web opening

specimens	*Opening dimension*		*Retrofit schemes*			
	Depth (mm)	*Length bo (mm)*	*Links number*	*Plates number*	*Retrofit zones*	*Plate size B X L X T (mm)*
TOSL-1	*100*	*100*	*4*	*4*	*around opening at same position*	*450 X 125 X 30*
TOSL-2	*100*	*200*	*4*	*4*		
TOSL-3	*100*	*300*	*4*	*4*		
TOAL-1	*100*	*100*	*4*	*4*	*around opening at same position*	*450 X 125 X 30*
TOAL-2	*100*	*200*	*4*	*4*		
TOAL-3	*100*	*300*	*4*	*4*		

Table – 5

Experimental results of solid specimens

Beam code	*Cracking torsional moment Mcr (KN.m)*	*Ultimate torsional moment Mu (KN.m)*	*Crack Twisting angle rad x10-5*	*Ultimate twisting angle rad x10-5*	*Increase of ultimate torque %*	*Strain in external links*
RS	*17.50*	*25.35*	*765*	*4814.40*	*---*	*---*
TS-1	*17.875*	*25.50*	*576.30*	*4386.00*	*---*	*---*
TSAL-1	*24.475*	*32.32*	*895.86*	*6550.32*	*26.80*	*400*
TSAL-2	*23.375*	*30.48*	*856.80*	*5500.30*	*19.53*	*200*
TSAL-3	*20.35*	*26.40*	*705.32*	*4895.20*	*3.05*	*400*
TSAL-4	*22.14*	*25.70*	*935.20*	*4200.00*	*0.70*	*400*
TSAL-5	*21.725*	*27.48*	*785.30*	*3743.40*	*7.77*	*400*
TSAL-6	*23.79*	*29.55*	*1071.00*	*4273.80*	*15.89*	*400*
TSSL-1	*22.55*	*29.57*	*900.00*	*4500.20*	*15.97*	*400*
TSSL-2	*20.625*	*27.88*	*744.60*	*4059.60*	*9.34*	*200*
TSSL-3	*21.87*	*26.00*	*945.30*	*4549.20*	*1.97*	*400*
TSSL-4	*22.68*	*25.50*	*96900*	*4200.30*	*0.00*	*400*
TSSU-5	*22.42*	*31.30*	*958.80*	*3500.20*	*22.75*	*400*

Table – 6

Experimental results of specimens with web opening

Beam code	*Cracking torsional moment Mcr (KN.m)*	*Ultimate torsional moment Mu (KN.m)*	*Crack Twisting angle rad x10-5*	*Ultimate twisting angle rad x10-5*	*Increase of ultimate torque %*	*Strain in external links*
TO-1	*15.40*	*22.016*	*581.4*	*3559.80*	*----*	*----*
TO-2	*12.925*	*16.62*	*520.20*	*2300*	*----*	*----*
TO-3	*9.90*	*15.90*	*459.00*	*2486.40*	*----*	*----*
TOAL-1	*19.525*	*26.56*	*700*	*4243.20*	*20.63*	*400*
TOAL-2	*16.225*	*21.20*	*703.41*	*3100.20*	*27.55*	*400*
TOAL-3	*15.8125*	*19.27*	*775.20*	*5018.40*	*21.19*	*400*
TOSL-1	*16.912*	*23.375*	*569.60*	*3760.20*	*6.17*	*400*
TOSL-2	*14.30*	*17.463*	*1320.54*	*2700*	*5.07*	*400*
TOSL-3	*13.475*	*16.21*	*1600.30*	*2750.20*	*2.00*	*400*

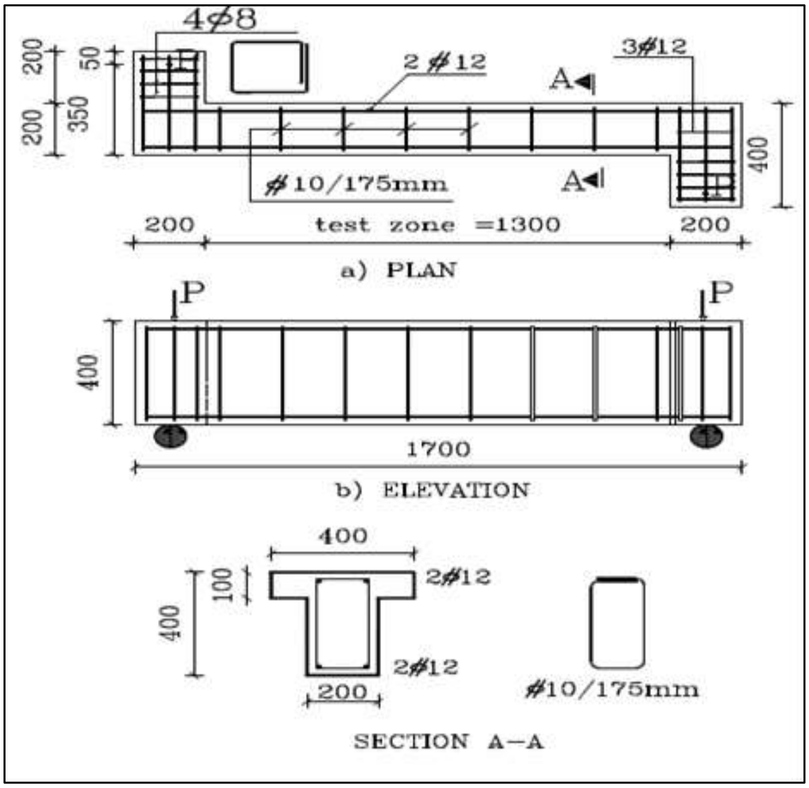

Fig. 1: (a) Dimensions and details of reinforcement of solid beams

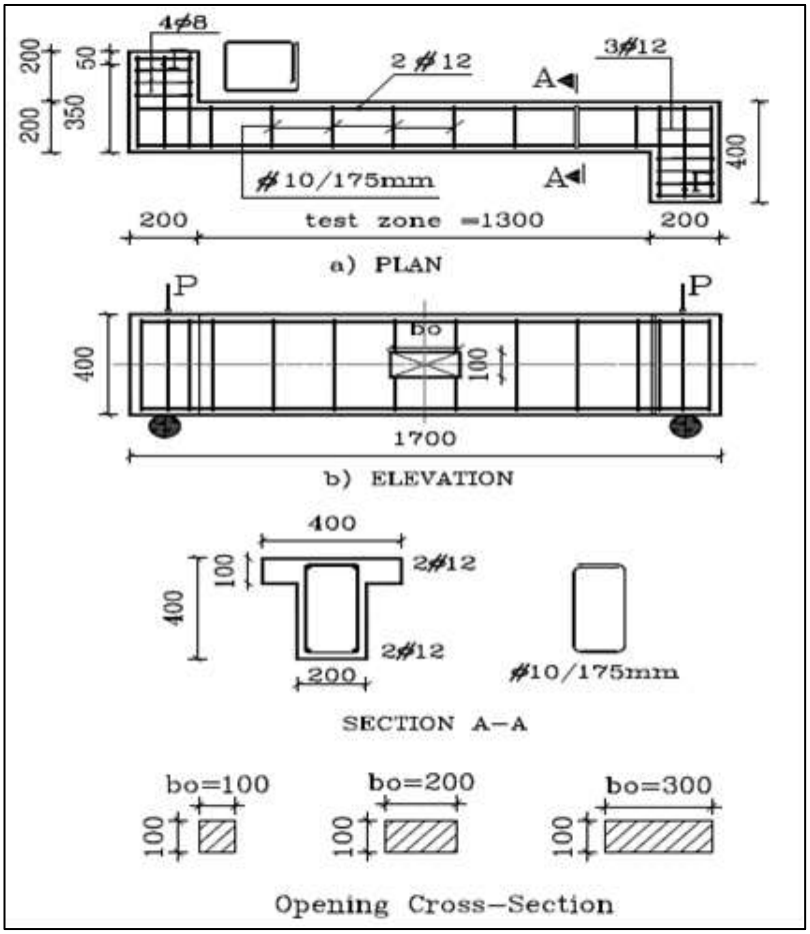

Fig. 1: (b) Dimensions and details of reinforcement of beams. With web opening

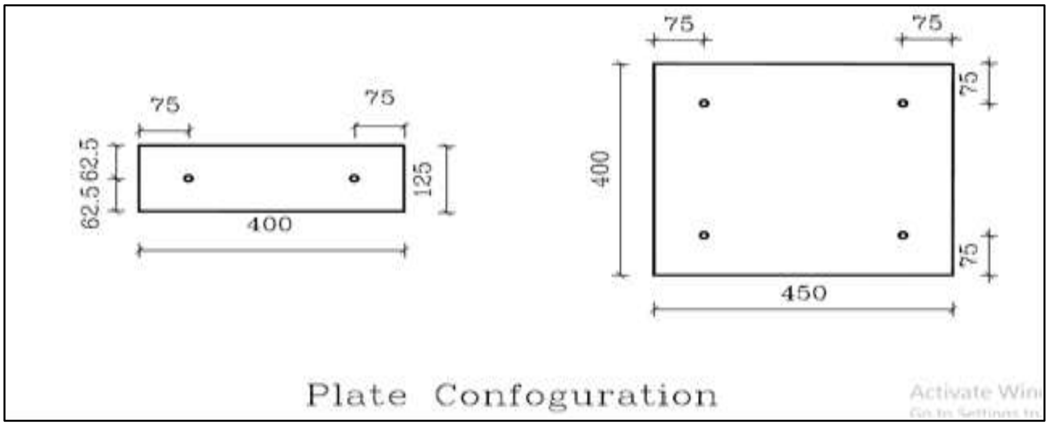

Fig. 2: Plates Configuration

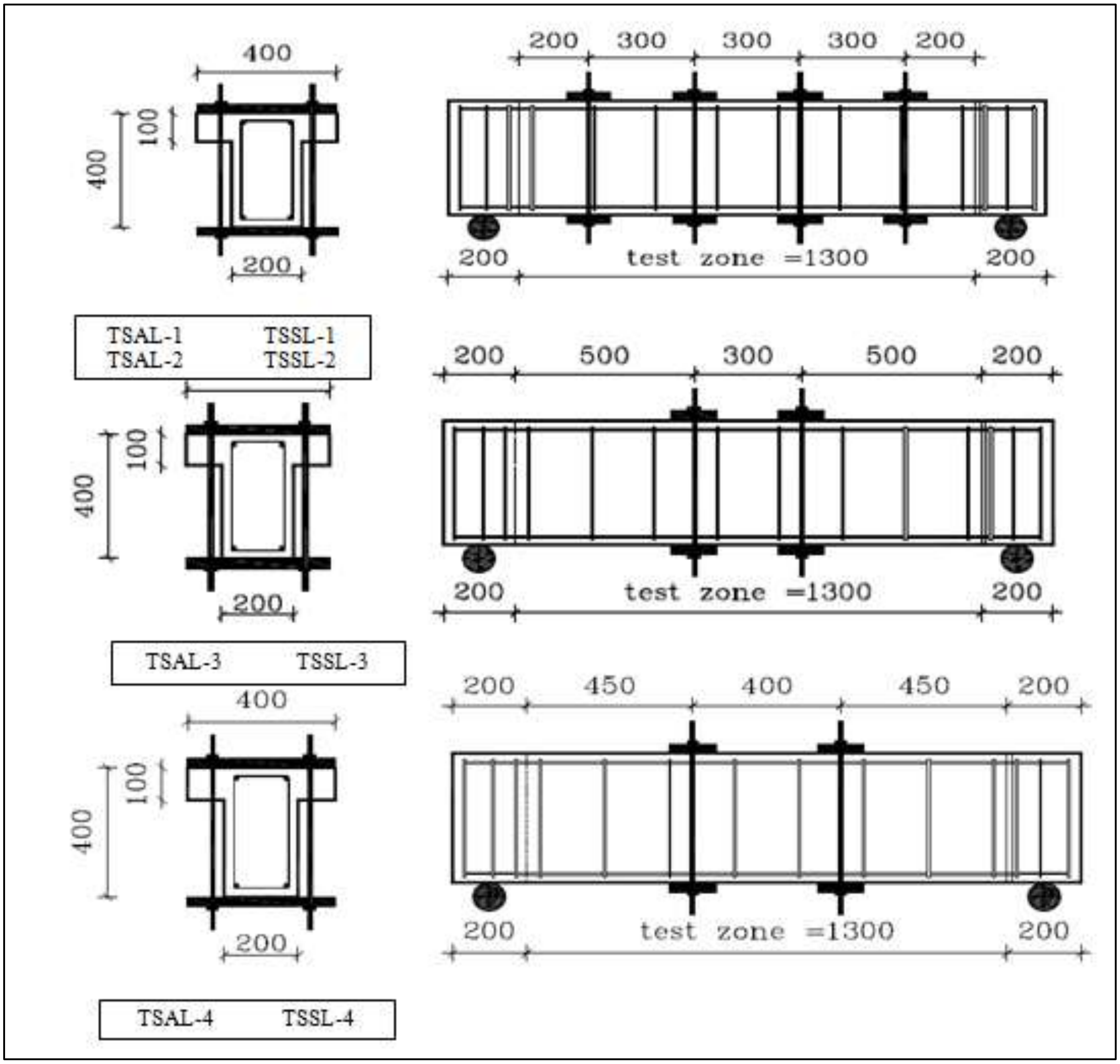

Fig. 3: (a) Different configuration of strengthening techniques

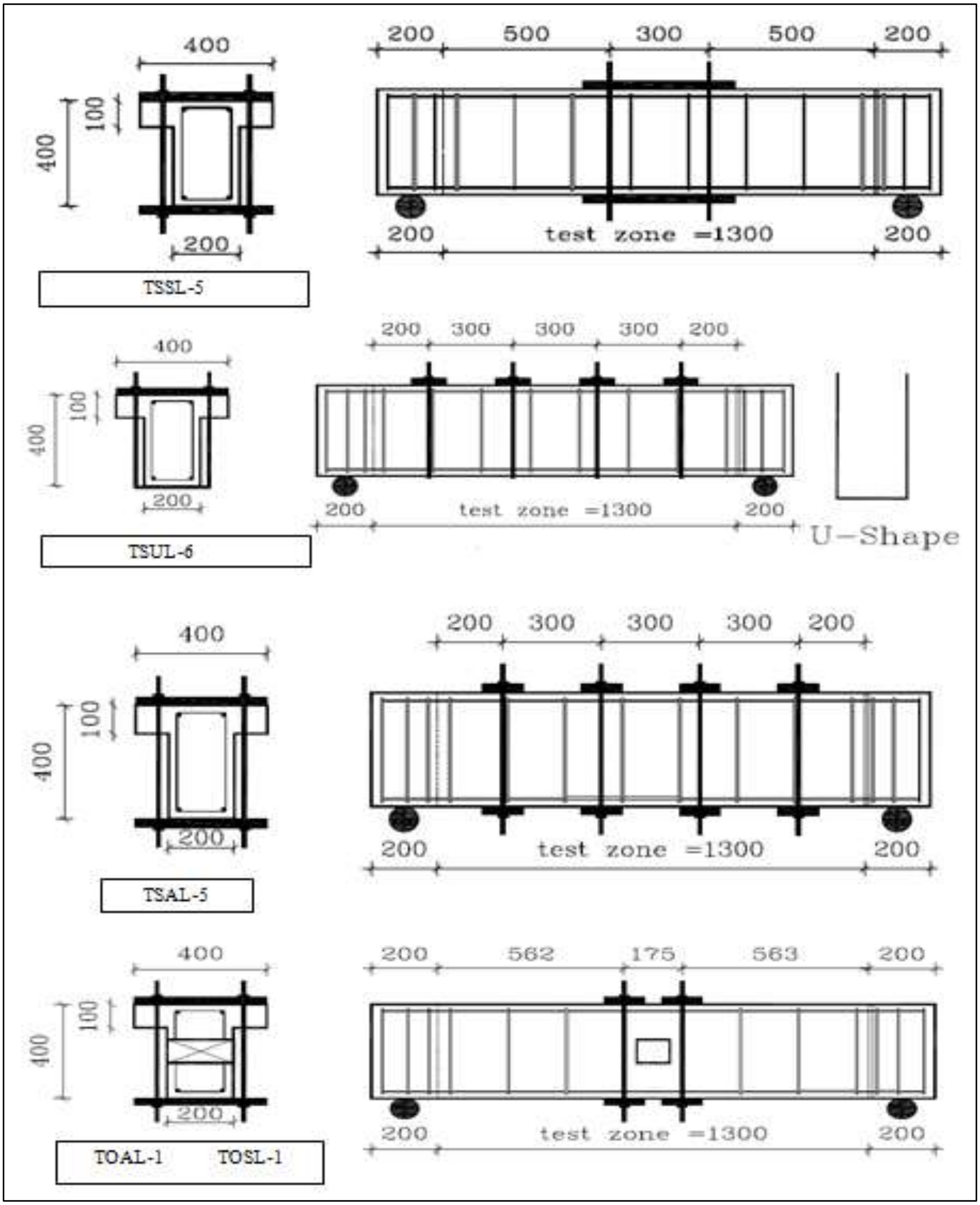

Fig. 3: (b) Different configuration of strengthening techniques

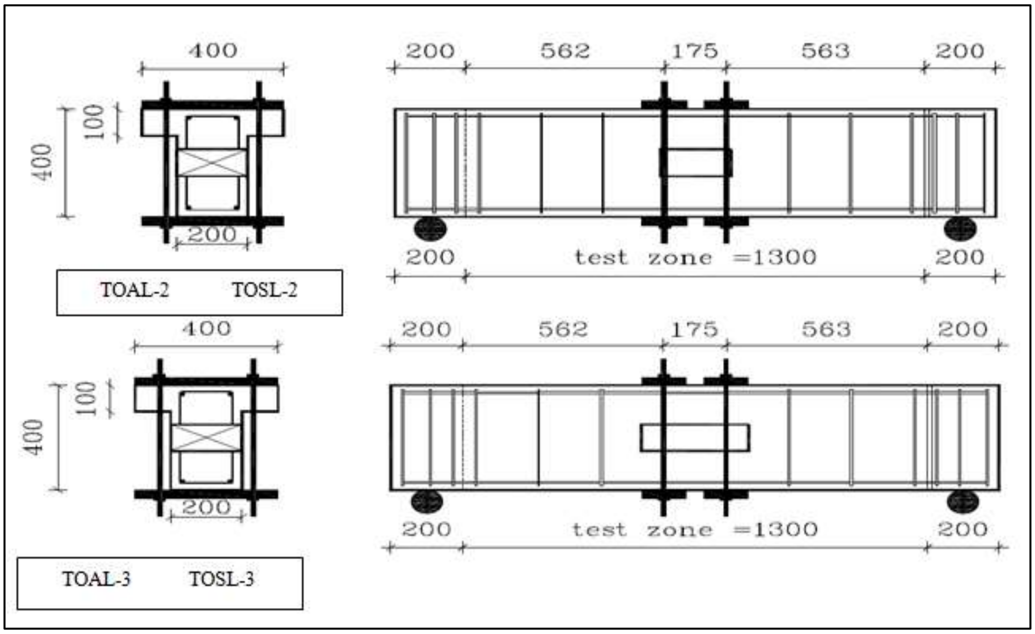

Fig. 3: (c) Different configuration of strengthening techniques

Fig. 4: wood mould

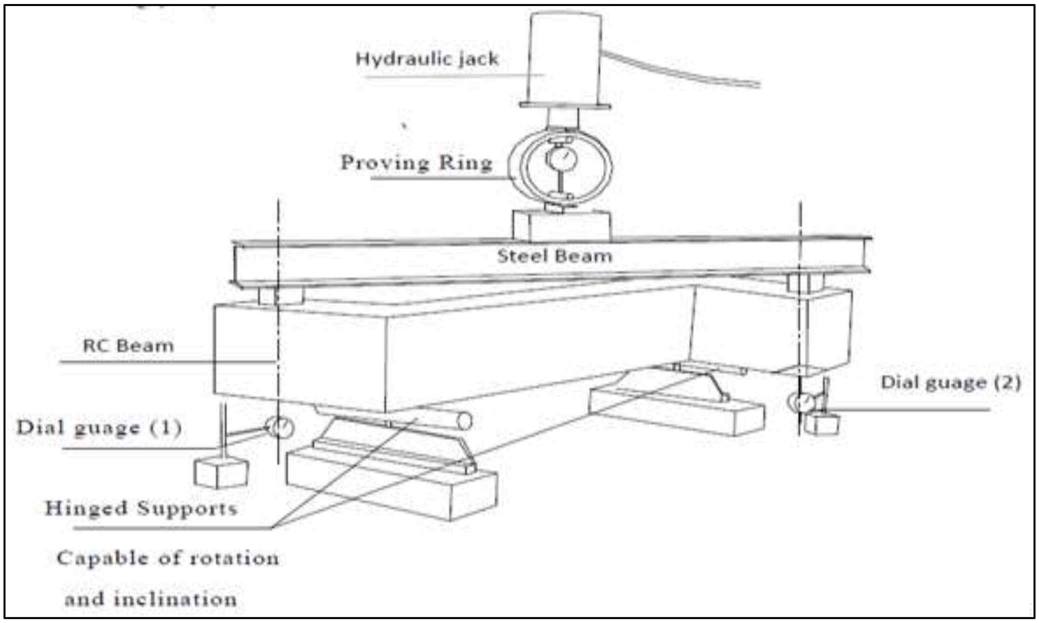

Fig. 5:

Fig. 6: (a) the crack pattern and failure modes for tested beams

Fig. 6: (b) the crack pattern and failure modes for tested beams

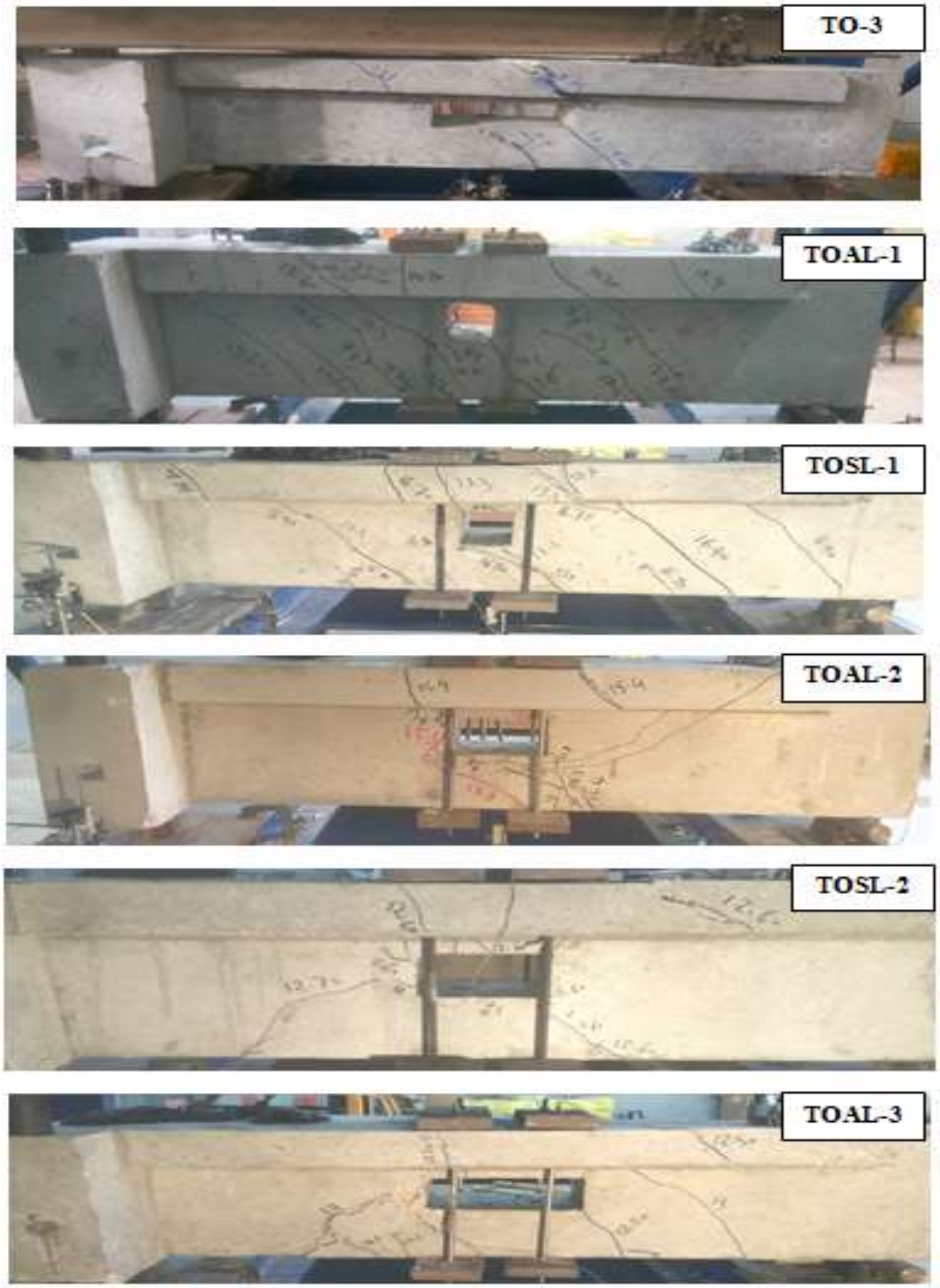

Fig. 6: (c) the crack pattern and failure modes for tested beams

Fig. 6: (d) the crack pattern and failure modes for tested beams

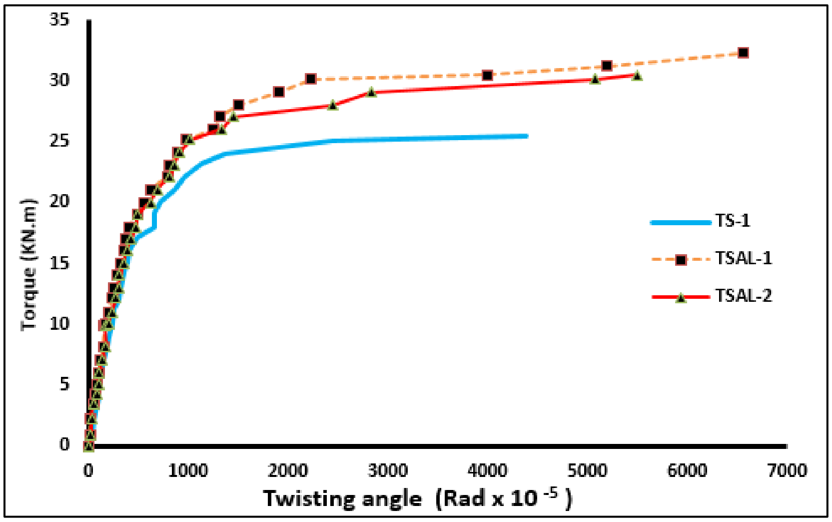

Fig. 7: Torque-Twisting angle relationship of group B strengthened with stainless steel links.

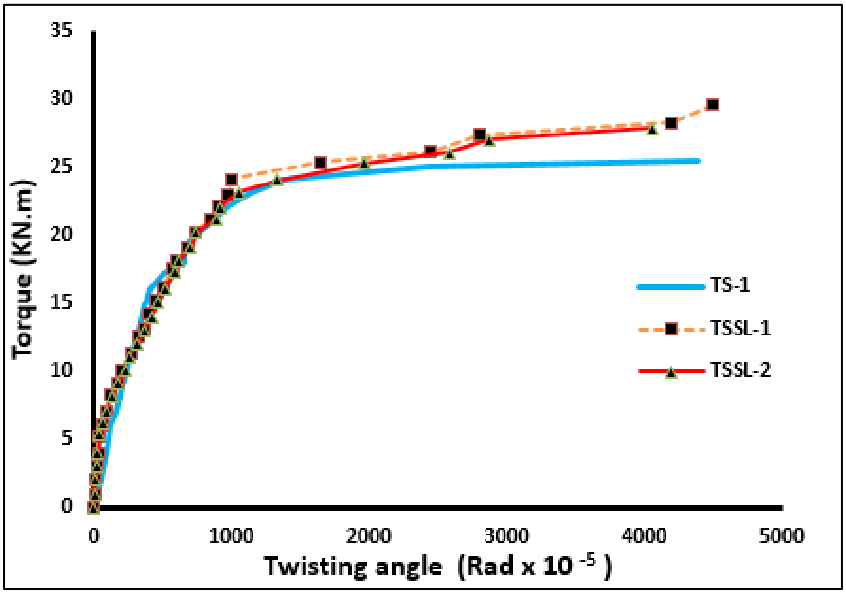

Fig. 8: Torque-Twisting angle relationship of group B strengthened with steel links

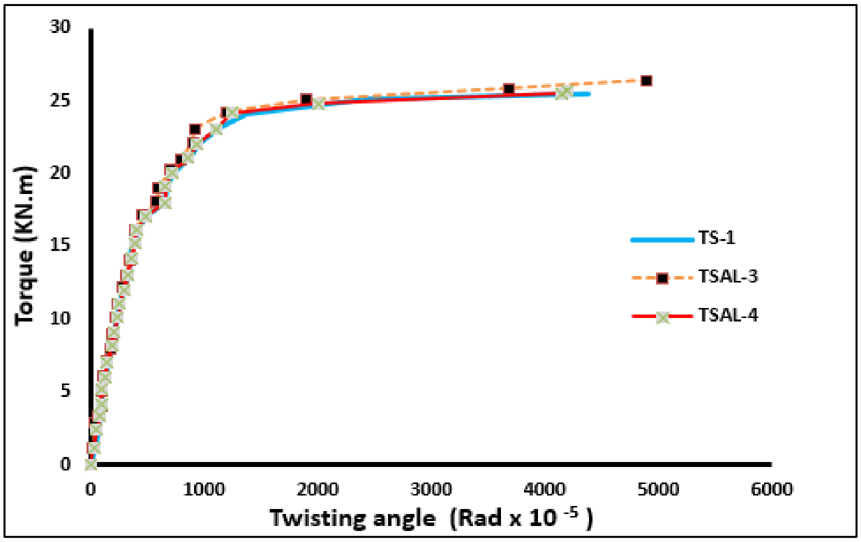

Fig. 9: Torque-Twisting angle relationship of group C strengthened with stainless steel links.

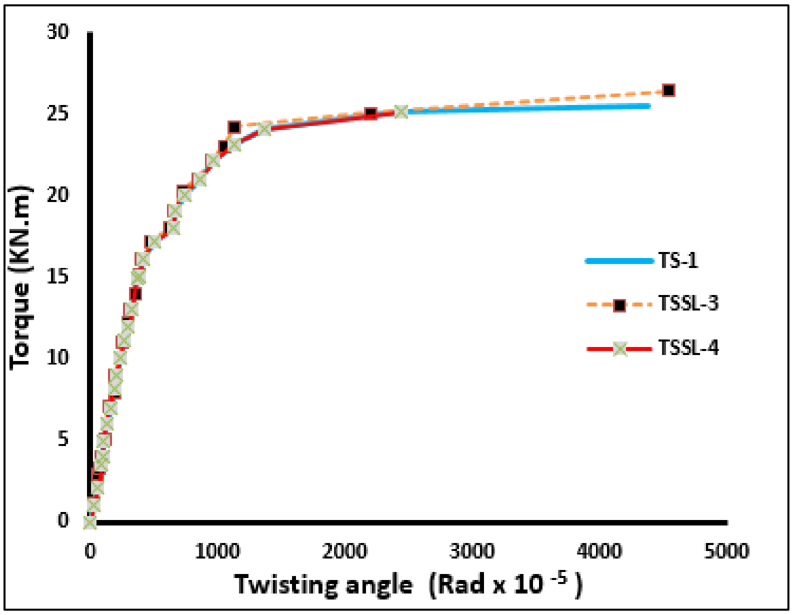

Fig. 10: Torque-Twisting angle relationship of group C strengthened with steel links

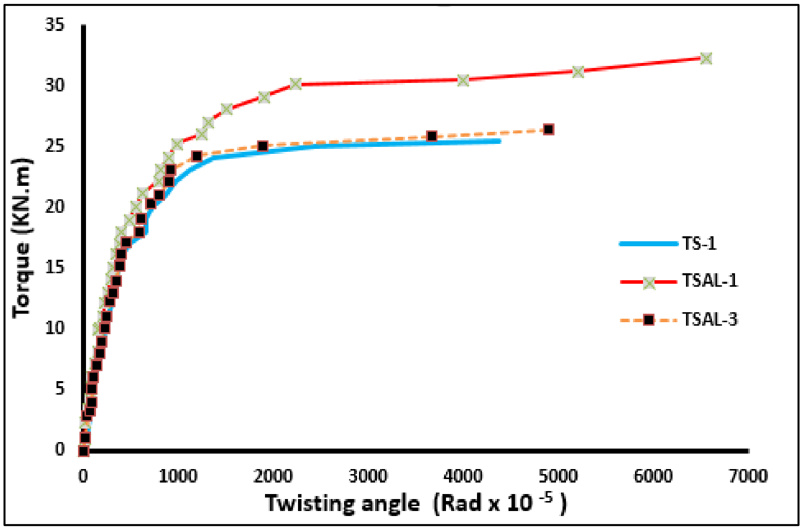

Fig. 11: Torque-Twisting angle relationship of group E strengthened with stainless steel links.

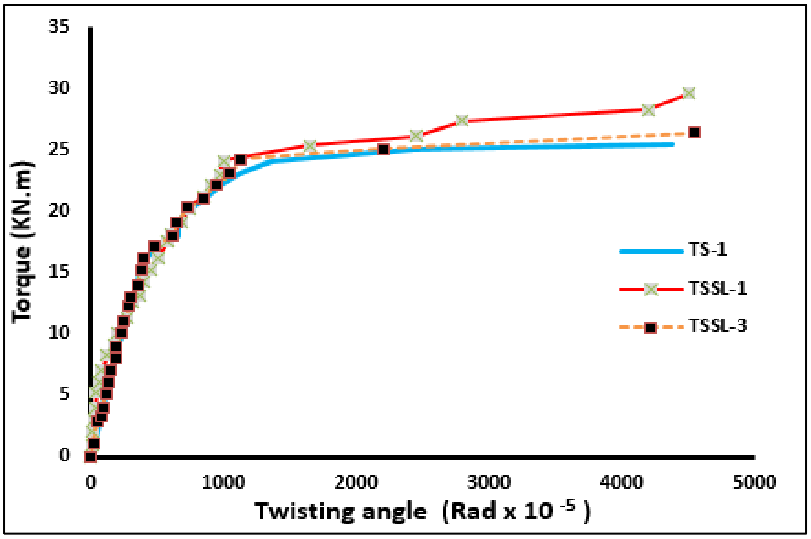

Fig. 12: Torque-Twisting angle relationship of group E strengthened with steel links

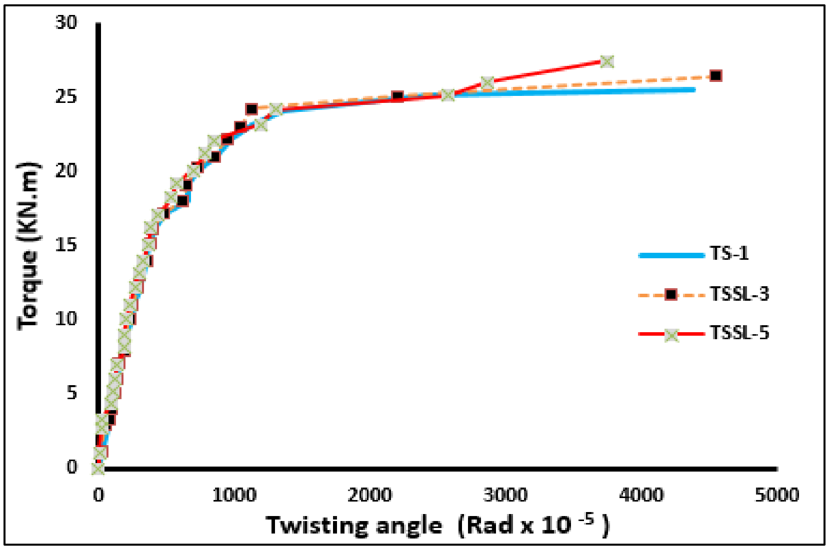

Fig. 13: Torque-Twisting angle relationship of group F strengthened with stainless steel links.

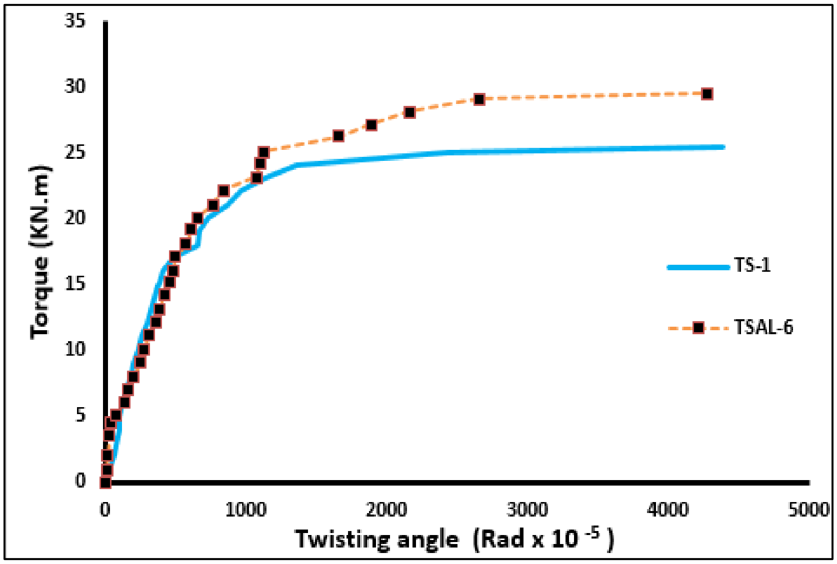

Fig. 14: Torque-Twisting angle relationship of group G strengthened with steel links

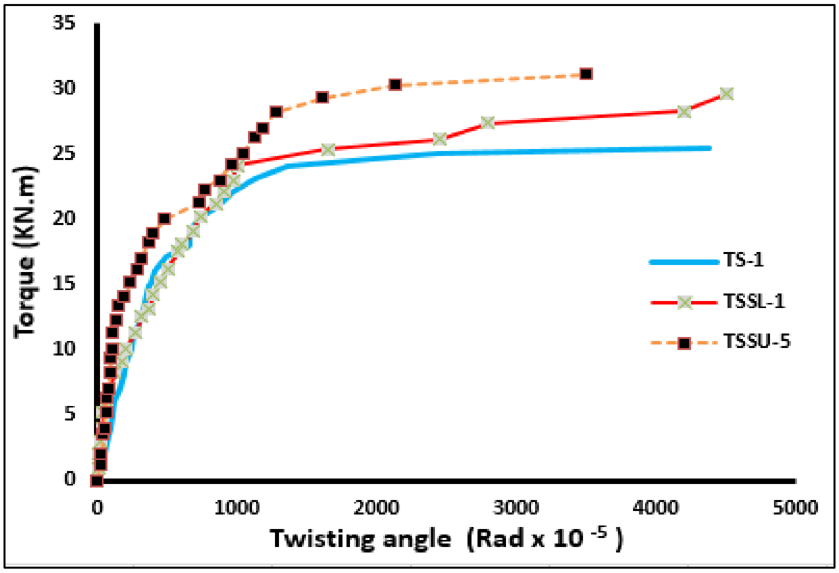

Fig. 15: Torque-Twisting angle relationship of group D strengthened with steel links.

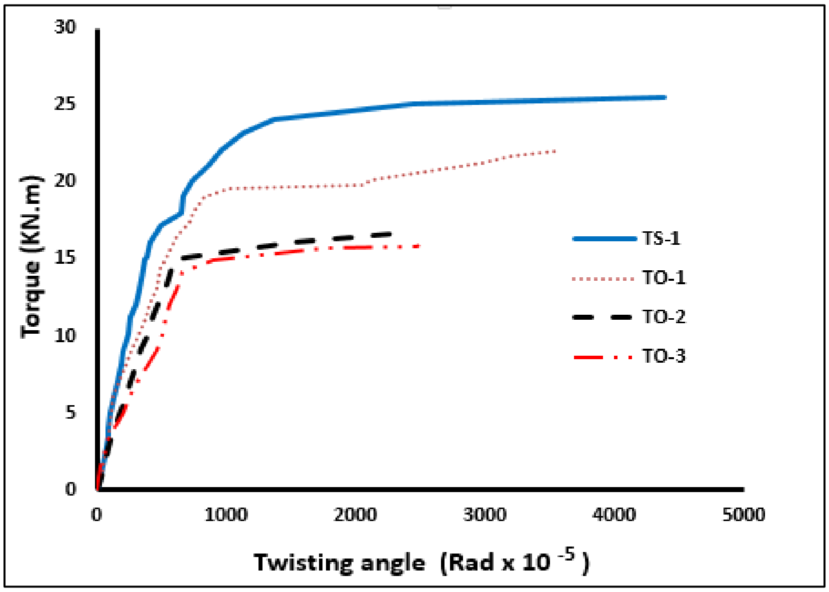

Fig. 16: Torque-Twisting angle relationship of control beams with web opening

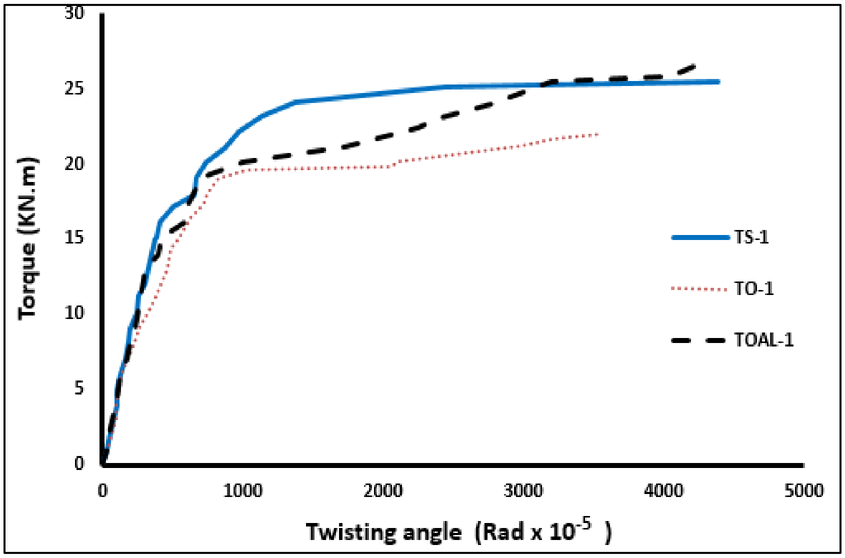

Fig. 17: Torque-Twisting angle relationship of beams with web opening (bo/d=1) Strengthened with stainless steel links

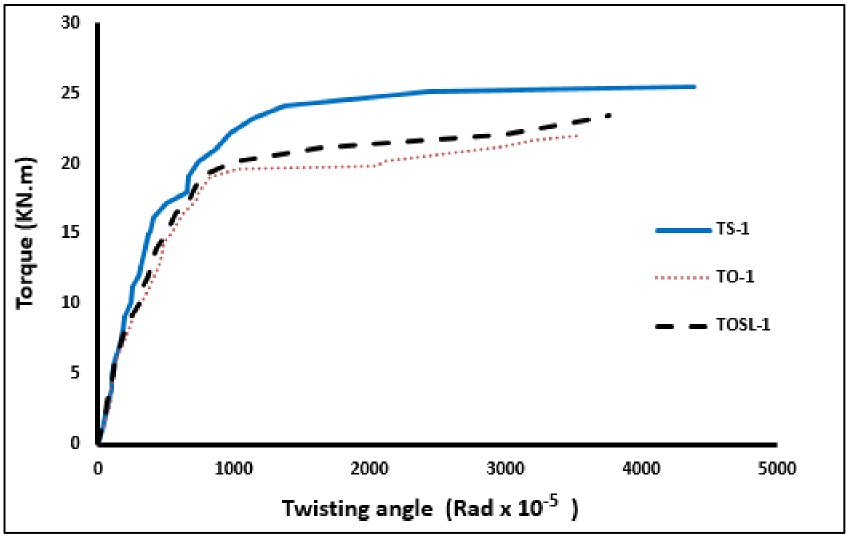

Fig. 18: Torque-Twisting angle relationship of beams with web opening (bo/d=1) strengthened with steel lin

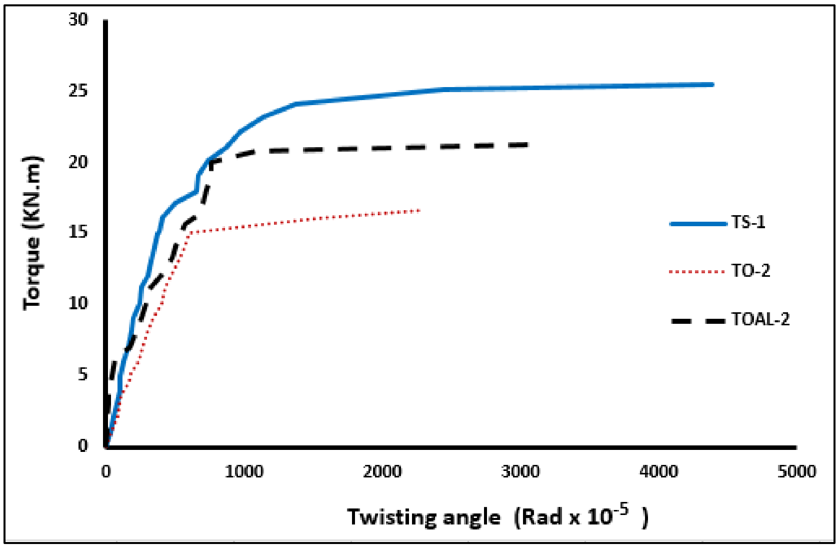

Fig. 19: Torque-Twisting angle relationship of beams with web opening (bo/d=2) Strengthened with stainless steel links

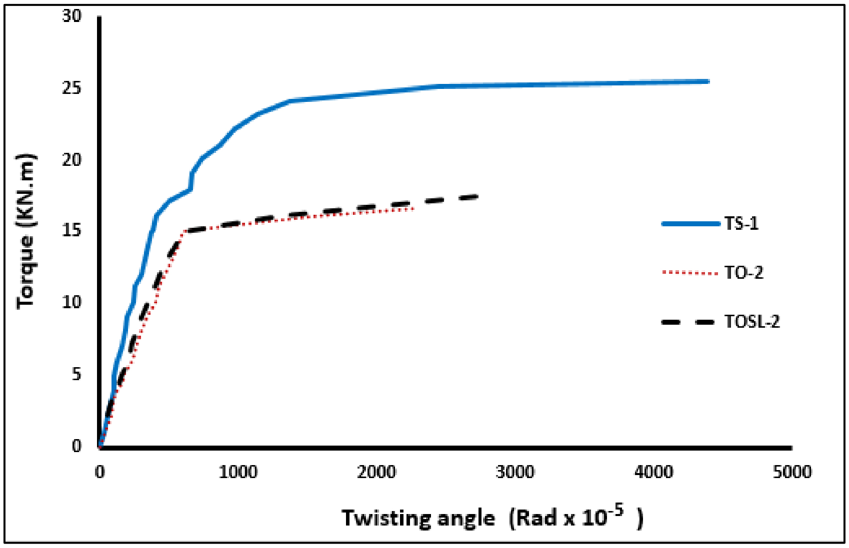

Fig. 20: Torque-Twisting angle relationship of beams with web opening (bo/d=2) strengthened with steel links

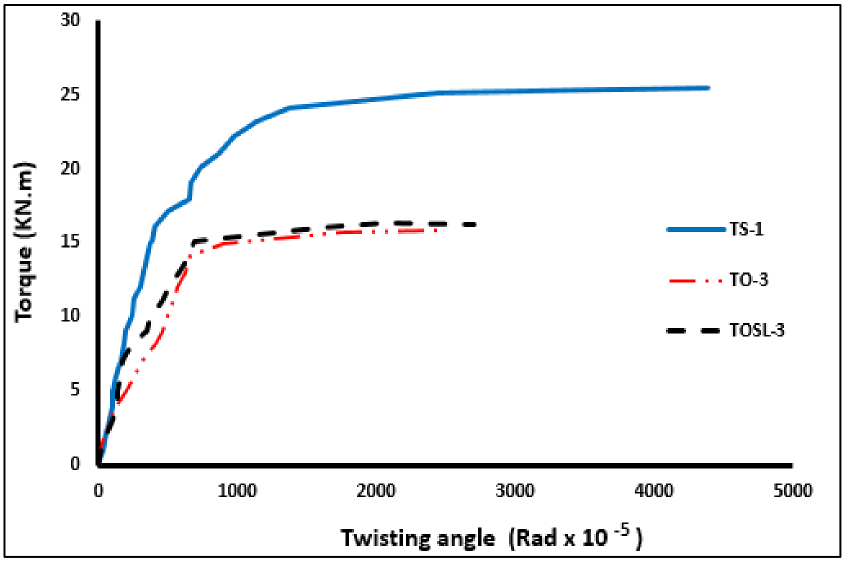

Fig. 21: Torque-Twisting angle relationship of beams with web opening (bo/d=3) Strengthened with stainless steel links

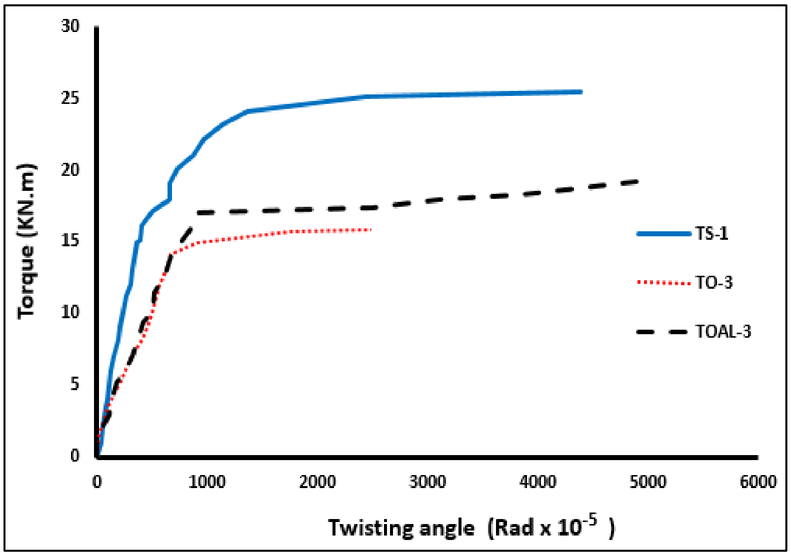

Fig. 22: Torque-Twisting angle relationship of beams with web opening (bo/d=3) strengthened with steel links