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Evaluation of Structural Behavior of Externally Prestressed Segmented Bridge with Shear Key under Torsion

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Abstract: Externally Prestressed Segmented (EPS) concrete beams are generally used in the construction of bridge structures. External Prestressed technique uses tendons that are placed completely outside the concrete section and attached to the concrete at anchorages and deviators only. Segmented bridge is a bridge built in short sections. Segmented bridge applies smart technique that is a part of an engineering management. EPS bridges are affected by combined stresses i.e., bending, shear, normal, and torsion stresses especially at the segments interface joints. Previous studies on EPS bridges did not include the effect of torsion in the load carrying capacity and other structural behavior. This paper presents an experimental investigation of the structural behavior of EPS bridged under combined bending, shear, normal, and torsion stresses. The aim of this paper is to improve the existing equation to include the effect of torsion in estimating the failure load of EPS bridge. A parametric study was carried out to investigate the effect of different external tendon layouts and different levels of torsion.

Keywords: Combined load, externally prestressed, segmented concrete bridge, torsion.

1. Introduction

Externally Prestressed Segmented (EPS) concrete box bridges have been successfully designed and used in structures all over the world. Un-bonded external prestressing tendons are used for many types of construction. The technique is also a useful for the rehabilitation and strengthening of existing structures.

The construction of segmented bridges with un-bonded tendons offers some advantages such as substantial economical savings due to the possibility of weather-independent segment production, shorter construction period, simple element assembly at job site, replaceability of tendons and optimal corrosion protection of the prestressing tendons and improved fatigue behaviour.

The analysis of a concrete member with an un-bonded external tendon is complicated because of the fact that strain compatibility of concrete and prestressing tendon at a section can no longer be applied. If friction is ignored, the force in the tendon is constant between the anchorages under all loads.

When the tendon is external, there is an additional difficulty due to the change in tendon eccentricity with applied loads. This change in eccentricity should be accounted for by considering the equilibrium of the structure at its deformed position. Since friction occurs only at deviators, the loss of tendon force due to friction is smaller compared to that in the internal tendons.

When the applied load increases, the external tendon slips at deviators resulting in redistribution of the tendon force, which affects the displacements of the member. Furthermore, the analysis of externally prestressed structure should also account for the cases where the tendon is bonded or un-bounded at the deviators. This is because, in the case where the external tendon is bonded at deviators, the force in the tendon is constant only between deviators whereas when the tendon is un-bonded (assuming no friction or free slip) the force in the tendon is constant along the entire length of the tendon between anchorages.

When a structure is constructed with precast segments assembled with external prestressing, the possible opening of the joints between the segments at high applied load should be considered in the analysis. Since internal reinforcements do not cross the joints, only external prestressing should carry the additional tension due to increase in loads. Thus, the force in the tendon is dependent on the magnitude of the joint opening.

2. Previous Studies

Many investigations on segmental structures with external prestressing were carried out in the last few decades, but most of them were restricted to a load combination of bending and shear such as in the research carried out by Below et al. (1975), Misic et al. (1978), and Rabbat and Solat (1987). Ramos and Aparicio (1996) and Turmo et al. (2005) developed a finite element method for the ultimate analysis of externally prestressed bridge (monolithic and segmental). The method evaluates the behavior of internal force and prestressing tendon under combined bending moment and shear. Three types of elements were generally considered to represent the concrete beam, the tendon and the joint in segmental construction. The representation included the material and geometry nonlinearities. The aim of the study was to obtain accurate values of stress increase of the tendons beyond the effective prestress, thus ignoring the effect of friction. A good correlation has been found between the results of the study and previous test results. Aparicio et al. (2002) presented the results of a test program on external prestressed concrete beams. Five monolithic and three segmental beams were tested in bending and in combined bending and shear. The ultimate load capacity of external prestressed beams has a significant influence on the tendon length as well as shear behavior of open joints. The comparison between the test results and those predicted by the numerical model gave differences lower than 15%. Turmo et al. (2006) discussed a study on the performance of concrete segmental bridges with shear keys focusing on the shear behavior of castellated dry joints under ultimate limit state conditions. The formula used to evaluate joint shear strength was compiled. The results obtained in these tests were compared with several design formulae for assessing the load-carrying capacity of dry interlocked joints without epoxy, identifying the formula that gave the best predictions.

Only a few investigations dealt with the influence of a combined loading of bending, shear, and torsion on the behavior of segmental structures such as by Kordina et al. (1984) and Falkner et al (1997). Huang et al. (2006) presented an analytical model to investigate the behavior of a prestressed segmental bridge with unbounded tendons under combined loading of torsion, bending, and shear. A modified skew bending model was developed to calculate the load-carrying capacity of segmental bridges subjected to combined forces. It was concluded that the ultimate bending and shear strength of monolithic and segmental girders were virtually the same. Only the torsional capacity of the segmental box girder was reduced.

Algorafi et al. (2007) presented a detailed review of the behavior of prestressed bridges under combined stresses with a particular emphasis on external prestressed segmental bridge beams. The study concluded that a comprehensive analytical and experimental research on SEP bridges and found that the bridges were under stresses resulting from combined bending, shear, normal and torsion forces.

Algorafi et al. (2010) and Algorafi (2011) presented a series of tests that were conducted to study the effect of torsion, joint type and tendon layout on the behavior of external prestressed segmental concrete box beams. The beams behavior was evaluated in terms of vertical deformation, twist angle, segment opening, tendon strain, load capacity and failure mode. The studies found that the structural behavior of EPS beams was significantly affected by torsion.

A number of researches had investigated the characteristics of external prestressed segmented beams under shear force or combination of bending and shear. However, there is insufficient research work on the characteristics of external prestressed segmented box bridge under combined bending moment, shear force, normal force and torsion including the effect of various parameters such as tendon layout and joint types. The currently used AASHTO design equation does not consider the effect of combined bending moment, shear force, normal force and torsion to estimate the EPS beam failure load capacity. Therefore, there is a need for more research work to investigate the behavior of externally prestressed segmented box bridge under this combined loading which includes torsion.

In this paper, the research of Algorafi et al. (2010) is extended to develop a new equation to evaluate the capacity of segment joint under combined loading (bending moment, shear force and torsion). It depended on the results of experiments of Algorafi et al. (2010) to improve the existing equation to evaluate the capacity of EPS bridge under combined loading.

3. Method

3.1. Experimental Program

To investigate the effect of torsion, two series of EPS beams (with different tendon layouts) under three vertical load cases (different load eccentricities) were tested. Details of the 6 beams are shown in Table 1. Each beam had three segments (two symmetrical edge segments and one middle segment) as shown in Fig. 1. The dimensions and reinforcement details are shown in Fig. 2. Double 7 wire of 0.5 inch diameter strand with external prestressing tendons (ASTM A 416-85 Grade 270) were used which were made in contact with the beam at anchorages and deviator only (Fig. 1). The area of each tendon was 98.7 mm2 (Algorafi et al. 2010).

The effect of the different parameters were studied to investigate the load at onset point of nonlinearity, joint opening load, failure load, twist angle and failure mechanism of EPS bridges. The parameters are: tendon layout (straight and harp) and the level of torsion (applied by providing eccentricity of 0 mm, 100 mm and 200 mm).

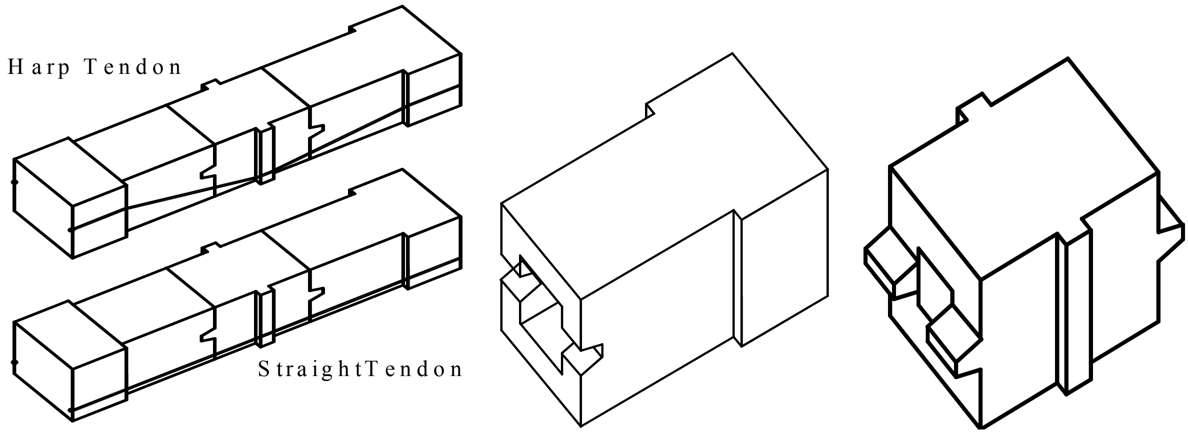
3.2. Test Setup and Instrumentation

The assembly of each beam was first done by arranging the segments close together on temporary supports. After that the two prestressed tendons were laid through the anchorages and deviator.

Two thick steel plates (600mm X 600mm X 20mm) were placed at the end of the edge segments. The steel plates were used to ensure a uniform distribution of prestress forces on the beams. Each beam was loaded with three point load with 2.4m span length as shown in Fig. 3. The prestress load was applied using a 30 kN capacity jack at each tendon. The vertical load was applied using a 500 kN jack capacity as shown in Fig. 3.

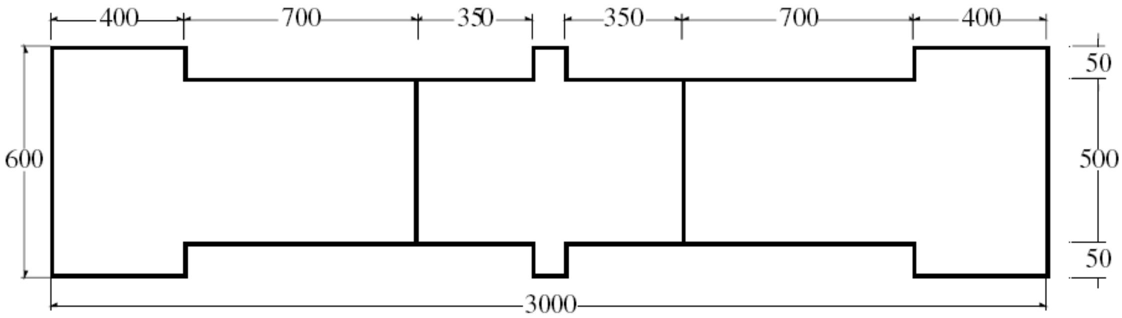
The supporting arrangement at the bottom of the beam was designed to simulate hinge support by using two solid steel shaft of 50 mm diameter. However, both ends of the beam were fixed against rotation about beam axis using the frame as shown in Fig. 3.

Horizontal and vertical deformations were measured using LVDT as well as mechanical dial gauges placed at different locations of the beam. Strain was measured by strain gauges fixed at each face of the beam at different location as shown in Fig. 4.

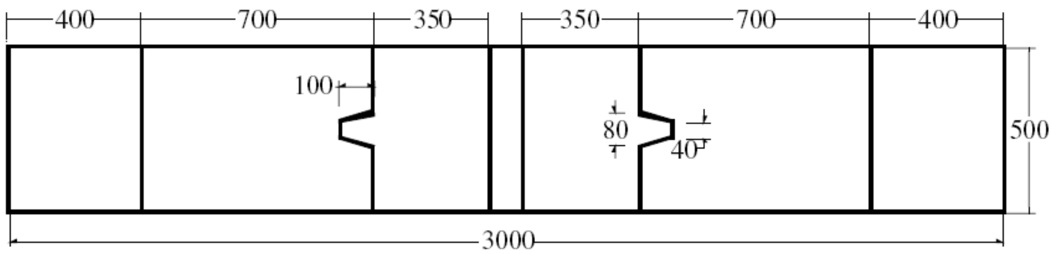


Beam Edge segments Middle segments

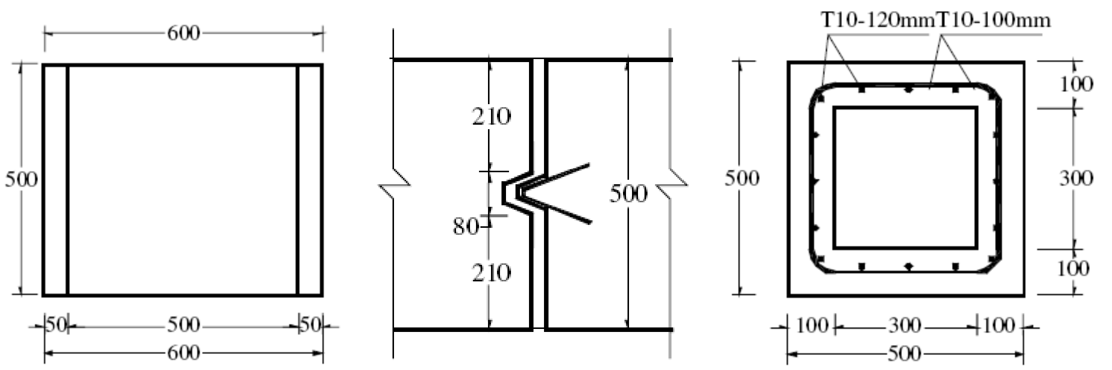
Fig. 1. Isometric view of beams and segments



(a) Plan view of beam



(b) Side view of beam



c) End view of beam d) Shear key reinforcement e) Reinforcement of beam

(Dimensions in mm)

Fig. 2. Beam dimensions and reinforcement

Table 1(a). Property of materials, tendon layout and load case in test beams

Beam No.		Concrete Compressive Strength (MPa)	Concrete Modulus of Elasticity (MPa)	Tendon Layout	Load Eccentricity (mm)
1	C1	49	34000	Straight	0
2	C2	47	34000	Straight	100 mm
3	C3	49	34500	Straight	200 mm
4	D1	47	34000	Harp	0
5	D2	47	34000	Harp	100 mm
6	D3	43	34500	Harp	200 mm

Yield Strength and Modulus of Elasticity of reinforcement bars and prestressed tendons were 420 MPa, 200 GPa and 1700 MPa, 200 GPa respectively.

Table 1(b). Property of materials, tendon layout and load case in test beams

Beam	Area of flat joint m^2	Area of shear key m^2	Prestressed Load kN	Tendon inclination α. rad
C1	0.15	0.009	82	0
C2	0.15	0.009	77	0
C3	0.15	0.01	87	0
D1	0.15	0.01	93	0.1351
D2	0.15	0.01	74	0.1351
D3	0.15	0.009	93	0.1351

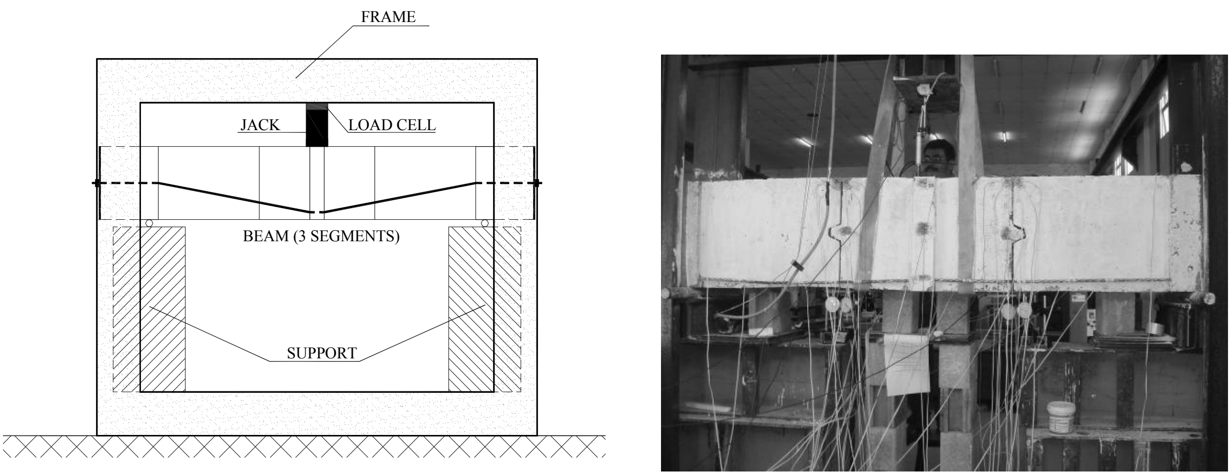


Fig. 3. Test setup

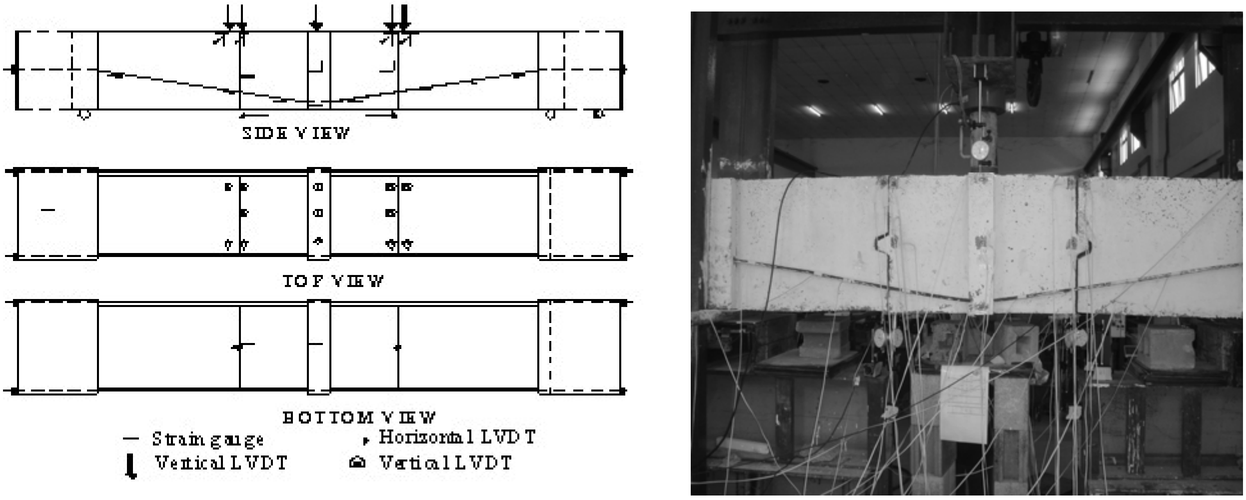
3.4. Results

Algorafi et al. (2010) presented the results of the experimental investigations of the structural behavior of EPS bridge beams under combined stresses, i.e. bending, shear and torsional stresses. The behavior of the beams was evaluated in terms of vertical deformation, twist angle, opening of segment, tendon strain, load capacity and failure mode. The structural behavior of EPS beams was significantly affected by torsion. Table 2 summarizes the part of the test results which used to propose a new equation.

4. Modification of Existing Equation to Estimate the Failure Load

The existing equations in design codes are limited to estimate the failure load of externally prestressed segmented beam under combined bending moment and shear force only. The ultimate load depends on safety factors as specified by the code requirements. In the present paper, the existing equation to predict the failure load was modified by including the effect of torsion.

The universally accepted theory to evaluate the shear strength of shear keys considers that the shear stresses are transmitted across the joint through two qualitatively and quantitatively different mechanisms. The first mechanism represents the friction resistance that arises when two flat and compressed surfaces attempt to slide one against the other. This resistance is proportional to the actuating compression and the corresponding proportionality factor is called the friction coefficient, μ1. The second mechanism considers the support effect of the castellated shear keys. These keys permit the shear transfer when there is contact between them, behaving like small plain concrete corbels. The shear strength of the keys by surface area is called cohesion, c. If compression stresses, σn, exist, then the keys turn out to be small prestressed concrete corbels, increasing the ultimate shear capacity with compression. The corresponding proportionality factor is called internal friction, μ2 (Turmo 2006).



(a) Transducer arrangement

(b) Typical experimental setup for test beam

Fig. 4. A transducer arrangement and a typical experimental test beam set up

Table 2. Summaries of deflection characteristics of all beams

Beam	C1	C2	C3	D1	D2	D3
Failure load (kN)	190	150	159	161*	172	160

* The ultimate load of beam D1 not exist

The formulae that best predicts the load carrying capacity of EPS bridges was theoretically mentioned by Turmo (2005) and Aparicio (2002) which was recommended by the AASHTO as shown in Eq. (1) below

$$V_c = (\mu_1 \times A_{sm} \times \sigma_n) + A_{key} \times \sqrt{f_{cu}}(\mu_2 \times \sigma_n + C) \quad (1)$$

Where

σn is average compressive stress across the joint (MPa)

Asm is area of contact between smooth surfaces in the failure plane (mm^2)

fcu is characteristic concrete compressive strength (MPa)

Akey is minimum area of the base of all shear keys in the failure plane (mm2)

μ1 is the friction coefficient between concrete at the segment joint

μ2 is the friction coefficient between concrete at the shear key

C is the shear strength of the keys

Fig. 5 shows the general case of EPS beam. The beam has shear key joint with inclined tendon and α angle.

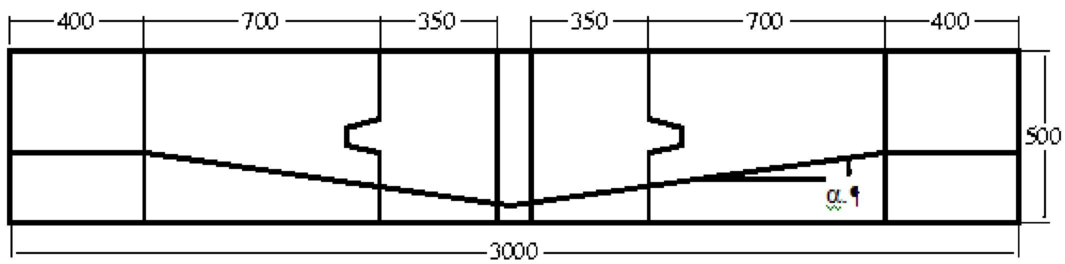


Fig. 5. General case of EPS Beam

However the existing equation was improved to Eq. (2) below to consider the effect of tendon layout and the affect of combined bending moment, shear force and torsion.

$$V_c = (\mu_1 \times A_{sm} \times \sigma_n) + A_{key} \times \sqrt{f_{cu}}(\mu_2 \times \times \sigma_n + C) + 2N \times \sin\alpha \quad (2)$$

Where

α is the tendon inclination as shown Fig. 6

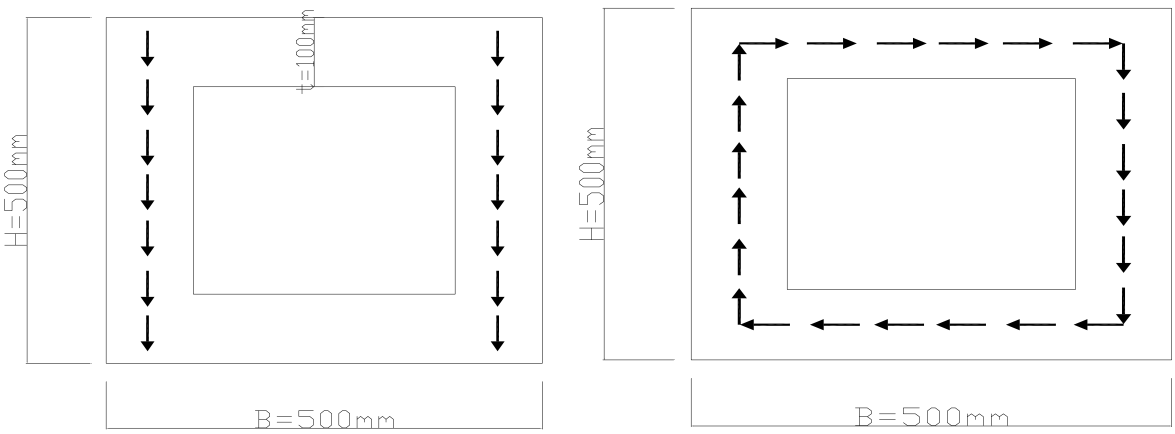
N is average tendon force (kN)

Eq. (2) has three terms: the first term represents the contribution of resisting shear capacity of flat joint; the second term represents the contribution of resisting shear capacity of shear key and the last term (which was modified by the author) represents the contribution of the vertical component of incline tendon resisting the downward vertical applied load. However, for beam with straight tendon layout the third term becomes zero.

The result of the 6 EPS beams were used to obtain the reasonable values of the three coefficients (*µ1*, *µ2*, *C*) and to estimate the shear capacity of EPS beam under combined load of bending moment, shear force, normal force and torsion.

The six beams have the same material and geometric property such as length, cross section reinforcement and tendon; however, the failure load for the beams was different. This is because of the effect of two parameters: value of torsion and tendon layout (straight and harp). Meanwhile, these parameters do not affect bending moment but affect shear. Consequently, it can be concluded that the critical failure of beams is due to shear failure of joint between segments rather than flexure failure.

On the one hand, the value of shear flow for applied vertical load can be calculated. Fig. 6 shows the applied shear flow in segment joints under both shear force and torsion. Eq. (3) presents the applied shear flow for both shear force and torsion. On the other hand, Eq. (4) calculates the resisting shear flow based on Eq. (2). Then, by equating the Eqs. (3) and (4), it can obtain the reasonable values of the three coefficients (*µ1*, *µ2*, *C*)



a) Shear flow due to shear force b) Shear flow due to torsion

Fig. 6. Shear flow for shear force and torsion

$$v_s = \frac{V}{A_{sm}} = \frac{0.5P_v}{A_{sm}} \Rightarrow f_s = v_s \times t = \frac{0.5P_v \times t}{A_{sm}} \quad (3a)$$

$$v_t = \frac{T}{2A_o \times t} = \frac{0.5P_v e}{2A_o \times t} \Rightarrow f_t = v_t \times t = \frac{0.5P_v e}{2A_o} \quad (3b)$$

$$f_R = \frac{V_R}{A_{sm}} \times t \quad (4)$$

Where

Ao is the closed area of centreline thickness (0.2025m),

t is the thickness of cross section (0.1 m).

vs shear stress due to shear force

vt shear stress due to torsion

V shear force

T torsion

f_s shear flow due to shear force

f_t shear flow due to shear force

e eccentricity

Using nonlinear regression analysis tool of SPSS program (version 16), the best value of the three coefficients generated are µ1=0.585, µ2 = 0.453, C=0.574, with R square equal to 0.99. So the resulting equation is shown below:

$$V_c = (0.585 \times A_{sm} \times \sigma_n) + A_{key} \times \sqrt{f_{cu}}(0.453 \times \sigma_n + 0.574) + 2N \times \sin\alpha \quad (5)$$

Table 3 summarizes the failure loads of the experimental and estimated values of failure load (Eq. (5)) for all beams. In conclusion, the proposed Eq. (5) estimates the shear capacity for EPS beam with error up to 4%. Furthermore, the correlation between the experimental and estimated values of failure load is found equal to 0.972. So it is concluded that there is good correlation between the experiments and the estimated failure load. The difference is because the existing equation was limited to predicted shear capacity under shear load only. However, the proposed equation was a general equation to predict shear capacity under combined loading.

Table 3: Summaries the Failure Load of beams

Beam	Estimated load (kN)	Experimental load (kN)	Difference
C1	191	190	1%
C2	146	150	3%
C3	158	159	1%
D1	237	-	-
D2	179	172	4%
D3	165	160	3%

5. Conclusion

Segmental box girder bridges with external post-tensioned are one of the major new developments in bridge engineering in the last years which is a part of engineering management. In contrast to monolithic constructions, the segmental bridge consists of small precast element stressed together by external tendons. The many advantages of this type of structure include offering fast and versatile construction, no disruption at ground level, high controlled quality and cost savings that have made them the preferred solution for many long elevated highways.

A series of tests were conducted to study the effect of torsion and tendon layout on the structural behavior of externally prestressed segmental concrete box beams.

An existing AASHTO equation was proposed to estimate the ultimate shear capacity of EPS beam subjected to combined bending moment, shear force, normal force and torsion. This proposed equation is applicable to predict the failure of the EPS bridge when the shear failure is governed. The proposed equation predicted the ultimate shear capacity for EPS beam with error up to 4% compared to experimental value. The predicted ultimate shear capacity from the modified equation was more conservative than the predicted ultimate shear capacity from existing equation up to 16%.

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