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Experimental Study on the Shear Transfer in Joints of Precast Segmental Bridge

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Abstract

This paper is concerned with the experimental study of shear strength and deformation of precast segmental bridge joints. The slip between the concrete segmental specimens, the failure mode of shear key and the horizontal movement between the segmental specimens are considered.

The test groups consisted of ten segmental specimens casting by using two types of concrete (normal and fibrous). All specimens have the same cross section and reinforcement. The concrete compressive strength was varied between (22.5MPa) and (33.6MPa). The prestressing reinforcement consists of two (12.7mm diameter) seven-wire strands with ultimate tensile strength of (f_u=1770MPa). The main parameters of the study were the number of shear keys, types of concrete and type of joint between segments.

Test results show that the ultimate load increased for specimens with one, two and three shear keys were about (16.27%), (50.68%) and (60.87%) of the maximum ultimate load of reference specimens (without shear key), respectively. Also the deflection as well as the slip between segments of specimens was decreased by increasing the number of shear keys. When the level of prestressing stresses increases from (175MPa) to (524.2MPa), the load carrying capacity of the tested specimens increased by about (40%).

الخلاصة

تهتم الدراسة الحالية بمقدار مقاومه القص وسلوك التشوه للمفاصل المستعملة في الجسور المجزئة على شكل قطع وكذلك تم دراسة تأثير الانزلاق بين القطع الخرسانيه، شكل الفشل عند المفاصل بالاضافة الى الإزاحة الافقيه للنماذج.

تضمنت الدراسة صب و فحص عشرة نماذج ، كل نموذج يتكون من ثلاثة قطع صبت باستعمال نوعين من الخرسانة (الاعتيادية، مع الالياف) ولها نفس الأبعاد وحديد التسليح مع مقاومه خرسانة تراوحت بين (22.5 الى 33.6 ميكاباسكال. تم استخدام ظفيرتين من حديد التسليح المسبق الإجهاد ذو مقاس (12.7mm)من نوع (7-Wire Strand) وبمقاومة قصوى للشد (f_u=1770 MPa). المتغيرات الرئيسية التي تم اعتمدها في البحث هي عدد مفاتيح القص، نوع الخرسانة المستخدمة و نوع المفصل بين قطع النموذج الواحد. أظهرت نتائج الفحص ان الحمل الأقصى يزداد للنماذج الحاوية على مفتاح قص واحد او مفتاحين او ثلاثة مفاتيح بمقدار (27. 16% , 50.68% و 87. 60 %) على التوالي نسبه للحمل الأقصى للنماذج المرجعية (التي لا تحتوي على مفاتيح قص).كذلك قل مقدار الهطول و الانزلاق بزيادة عدد المفاتيح. اما في حالة زيادة قوه السحب في حديد التسليح المسبق الإجهاد من (175MPa) الى (524.2MPa) فان الحمل الأقصى للنموذج زاد بمقدار (40 %).

1- Introduction

Bridges have been built since thousands of years. Nevertheless, new innovative, construction methods are still required. Precast concrete segmental hollow box girder bridges externally prestressed are one of the major developments in bridge construction (1).

Although many segmental bridges had been built so far, some significant design aspects still need further investigation. One is the construction and design of unreinforced dry joints between the precast segments. Furthermore, the effect of bowing of the segments during match-casting which may result in a gap between two adjacent segments on the behavior of a segmental construction is not known (2). A large number of post-tensioned of varying lengths have been constructed, resulting from the demand of an economical and safe design, fast, versatile and practical construction, and excellent serviceability. Segmental bridges are recognized as a solution to many bridge problems with superior durability, low life-cycle costs, and quality control readily achieved. The overall behavior, including the ultimate strength of segmental bridges, depends on the behavior of the joints between segments. Early forms of these bridges normally used single keys in the web section, and these could be reinforced in the key area. Current practice, however, is to use multiple keys that are generally unreinforced in the key zone, distributed over the height of the web and flanges, and provides an improved interlocking performance. These joints represent locations of discontinuity through which compression and shear forces are transmitted. The stiffness and shear strength of the joints between the precast segments can be weaker than those of adjacent monolithic sections within the segments. The keys in those joints serve three functions. The first is to align the segments during erection. The second is to transfer the shear force between segments during service, and the third is to ensure durability by protecting the prestressing tendons against corrosion where the tendons pass through the joints.There are two types of joints; dry and epoxy glued. Many investigations on dry and epoxy glued joints show that joints bonded with epoxy developed essentially the same strength as monolithic specimens and the design of keys as corbels using either ACI or PCI specifications is conservative(3,4). The benefit of using steel fiber reinforced concrete is also evaluated by casting and testing reinforced and SFRC panels with different levels of prestressing evaluating the behavior of castellated dry joints under direct shear (5). The cracking observed in the keys is wide-ranging corresponding to patterns that could involve high compressive stresses, high shear stresses and high local flexure in the key, Figure (1)The objectives of this study are to investigate the effect of types of joint (dry, epoxy), number of shear keys and type of concrete used on the behavior and load carrying capacity of reinforced concrete segmental specimens.

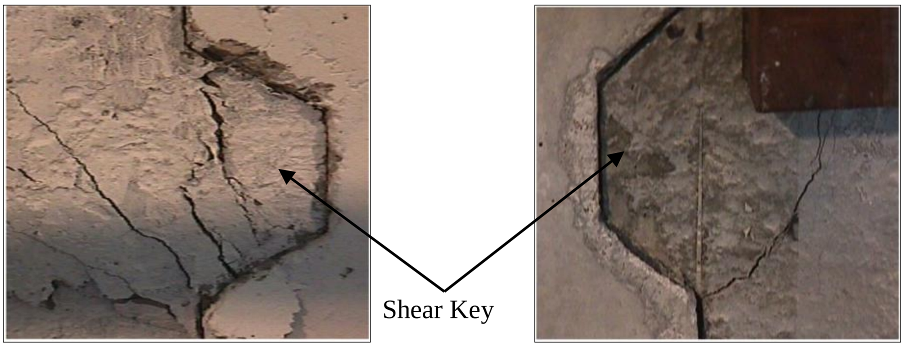

Figure (1) Crack Patterns of Shear Keys (Reported by Turmo et. al.)(5)

2- Experimental Work

2-1- Experimental Program

The experimental program consists of fabricating and testing of ten specimens, each specimen consist of three segments connected together by using two strands. All segmental specimens have the same dimensions and reinforcement. The segmental specimens have (650mm), (900mm) and (100 mm) for height, width and thick respectively, see Figure (2). The segmental specimens were divided into five groups as shown in Tables (1) and (2).

Table (1) Description of Groups

Group	Description
Group-1	Defined by two segmental specimens, Sg-1 and Sg-6, to study the effect of tension force in the prestressing steel strands. The specimens have the same number of shear keys and type of concrete.
Group-2	Defined by three segmental specimens, Sg-2, Sg-3 and Sg-4, to study the effect of type of concrete. The specimen has the same number of shear keys and tension force in the prestressing strands.
Group-3	Defined by four segmental specimens, Sg-4, Sg-5, Sg-6 and Sg-7, to study the effect of number of shear keys. The specimens have the same type of concrete and tension force in the prestressing strands.
Group-4	Defined by three segmental specimens, Sg-4, Sg-8 and Sg-9, to study the effect of type of bond at the joint (Epoxy or Dry). The specimens have the same number of shear keys, type of concrete and tension force in the prestressing strands.
Group-5	Defined by two segmental specimens, Sg-7 and Sg-10, to study the effect of friction in the joint (Greased or Dry). The specimen has the same type of concrete, and tension force in steel strand, and without shear keys.

Table (2) Details of the Tested Segmental Specimens

Specimen Designation	Group No.	Concrete Type	No. of Shear keys	Joint Type	Tensile Stress in Strands (MPa)
Sg-1	1	NSC	One	Dry	524
Sg-2	2	NSC	Two	Dry	175
Sg-3	2	SFRC	Two	Dry	175
Sg-4	2,3,4	NSC	Two	Dry	175
Sg-5	3	NSC	Three	Dry	175
Sg-6	1,3	NSC	One	Dry	175
Sg-7	3,5	NSC	None	Dry	175
Sg-8	4	NSC	Two	Dry	175
Sg-9	4	NSC	Two	Epoxy	175
Sg-10	5	NSC	None	Greasy	175

2-2-Materials and Mixes Properties

Material properties used in this study are: Ordinary Portland cement (Type-I) manufactured by Tasluga Cement Factory. Natural sand from (Al-Akhaidher) region was used for concrete mixes. The fine aggregate has (4.75mm) maximum size with a rounded-shape particles and smooth texture. Crushed gravel from (AL-Niba'ee) region with maximum size of (10mm) is used throughout the tests. One concrete mix proportion (cement: sand: gravel) of (1: 1.5: 3) by weight, with w/c of (0.45) has been used to produce concrete strength (f_c' =22.5MPa), for all segmental specimens, except specimens (Sg-2) which had a mix proportion of (1: 1.5: 2) by weight with w/c of (0.45) to produce concrete strength of (f_c' =33.6 MPa) and specimen (Sg-3) (SFRC) which had mix proportion of (1: 1.5: 3) by weight, with w/c of (0.45) and steel fibers with volume fraction of (V_f=0.75%) to produce concrete strength of (f_c' =28.2MPa). The segmental specimens were tested under uniform loading which applied directly on the middle segments which have dimensions of (650x300x100mm) as shown in Figure (2). Both, tested specimens and control specimens are cured under the same conditions for (28days). Mechanical properties of tested specimens are summarized in Table (3).

The prestressing reinforcement consists of two (ϕ12.7mm) seven-wires strands with (f_{py}=1570MPa), (f_{pu}=1770MPa), (A_{ps}=93mm²), and (E_s=195000MPa). While, the non-prestressing reinforcement that have been used in segmental specimens were (4ϕ16mm) in longitudinal direction, and (7ϕ12mm) for transverse direction (ties) as shown in figure (3).

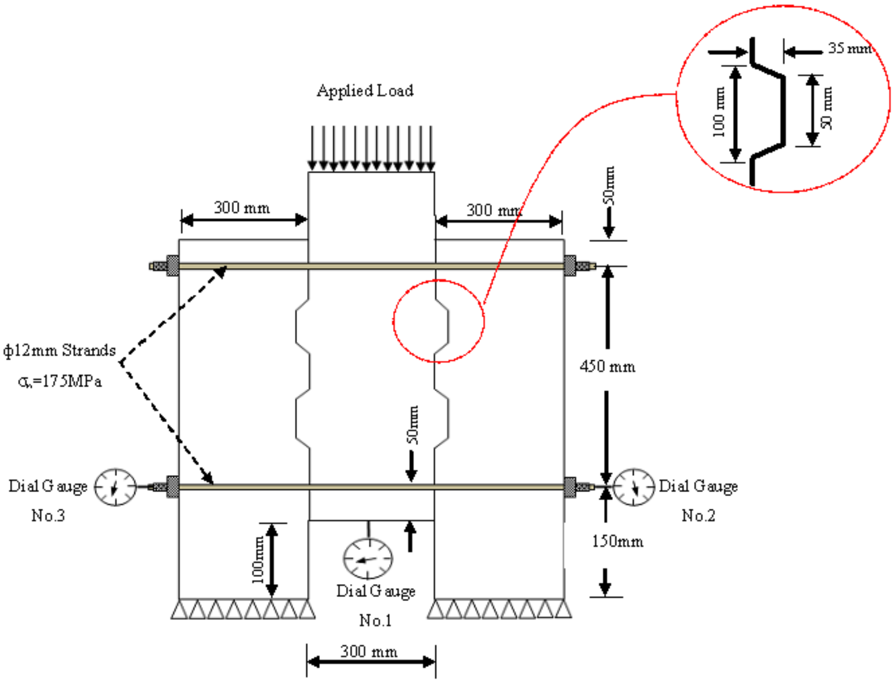

Figure (2) Details of Segmental Specimens

The yield tensile strength of reinforced bars with (ϕ16mm) and (ϕ12mm) were (f_y=537 N/mm^2) and (f_y=420 N/mm^2) respectively. Throughout this work, also, crimped mild carbon steel fibers with average length of (25mm), nominal diameter of (0.5mm), aspect ratio of (50) and yield strength of (1130MPa) were used with volume fraction of (V_f =0.75%).

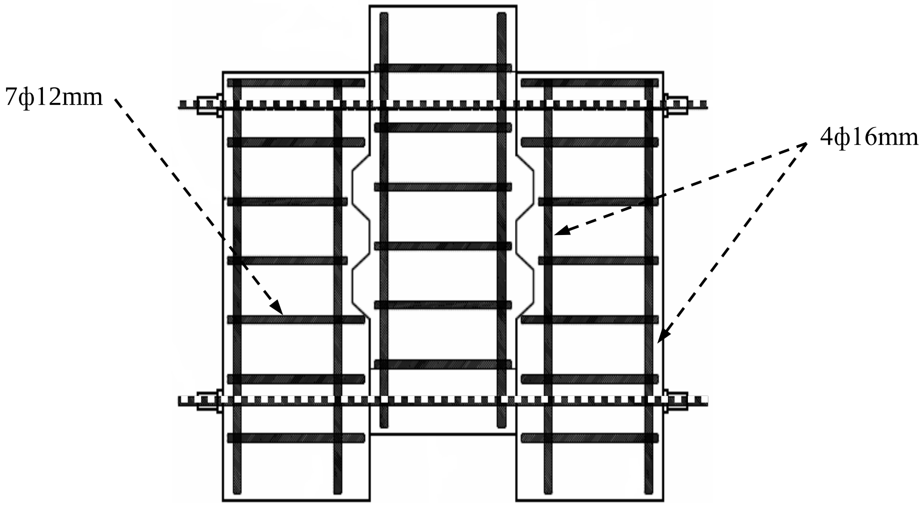

Figure (3) Non-Prestressing Reinforcement

Table (3) Concrete properties of Test Segmental Specimens

Specimen Designation	f_c' (MPa)	f_{cu} (MPa)	f_{ct} (MPa)	f_r (MPa)	f_c'/f_{cu}	E_c* (MPa)
Sg-1	24.17	32.22	4.81	3.21	0.75	23106.6
Sg-2	33.62	41.10	5.45	3.49	0.82	27251.9
Sg-3	28.16	34.77	5.38	2.97	0.81	24941
Sg-4	23.60	32.28	4.67	3.03	0.73	22832.5
Sg-5	23.51	31.77	4.46	3.08	0.74	22788.9
Sg-6	23.47	31.29	4.25	3.08	0.75	22769.5
Sg-7	22.57	32.24	4.33	3.13	0.70	22328.7
Sg-8	23.02	30.29	4.6	3.09	0.76	22550.2
Sg-9	22.46	30.35	4.41	3.14	0.74	22274.2
Sg-10	22.90	30.9	4.72	3.02	0.74	22491.4

* $E_c = 4700\sqrt{f_c'}$ ……. ACI-318(6)

Compressive strength test was carried out on (300x150mm) cylinders accordance to ASTM-C39-03(7), also, the compressive strength test of concrete were carried out on (150x150x150mm) cubes accordance to BS 1881: Part 116(8) . Tensile strength in flexural (modulus of rupture) and indirect tensile strength (splitting tensile strength) were carried out in accordance to ASTM-C78(9) and ASTM C496-79 (10) respectively.

2-3- Instrumentation and Test Procedure

The prestressing force (prestressing tensile force) in strands (cables) were take place by using Hydraulic Machine, as shown in Figure (4). It consists of a system of a hydraulic joints, electrical pump, main measuring gage to observe the applied pressure with (bar unit) that is graduated (0 to 600 bars), and main steel jack operating by an electrical manual control that contains interior nuts as cone-shape working as a pincer and pinches the strand after entrance through it. Then, the stressing force is applied at stages or (increments), while the machine is operating.

During the test, the applied load, the corresponding slip (displacement at middle segmental specimens) and lateral movement between segmental specimens are measured using the universal testing machine and dial gauges (reading to 0.01mm); then, the outputs (readings) from each tested segmental specimens are collected and used to draw load-Slip curves. Two dial gauges (reading to 0.01mm) are used to measure the slip or relative movement between the three concrete parts. One dial gauge is used to measure the slip (Vertical displacement) which was put under the center of the specimens. The locations of the various gauges are shown in Figures (2) and (5).

Figure (4) Prestressing Hydraulic Machine and Prestressing Process

All tests are carried out initially under the condition of load control of (5kN) increments, and then reached to the ultimate load. The same test procedure is followed for all segmental specimens. At the beginning of each test, a small load is applied (about 2kN) to seat the supports and loading system, then the load is released and reloading is carried out in a slow rate. Sides of each segmental specimen are painted with white color to expose the formation of cracks.

Figure (5) Setup of Segmental Specimen

3- Results and Discussion

In this study, ten segmental specimens were tested as mentioned before. These segmental specimens were made with different types of concrete, number of shear keys, tensile stress in prestressing strands and types of joints at interface between segments. According to these variables, the recorded data, general behavior, mode of failure and test observations are reported as well as recognizing the effects of various parameters on the segmental specimens. Photographs for the tested segmental specimen are taken to show the crack pattern and other details.

3-1- First Crack and Ultimate Loads

Test result shows that when adding steel fibers to concrete with (V_f = 0.75%), the ultimate loads is increased by about (5.5 %). As the number of shear keys increases, an increase in value of the ultimate load has been obtained. When the number of shear keys increased from (0) to (1), an average increase in the cracking load of about (19.44%) was obtained. While, when the number of shear keys increased from (1) to (2), an average increase in the cracking load of about (69.8 %) was achieved. When number of shear keys increased from (2) to (3) the average increase in the cracking load was about (26.03%).

Table (4) First Crack, Ultimate load and Mode of Failure

Group No.	Specimen Designation	(P_{cr}) kN	(P_u) kN	(P_{cr})/ (P_u)	Mode of Failure
1	Sg-1	7.5	365	2.05	Shear in key
	Sg-6	5.0	215	2.33	Shear in key
2	Sg-2	6.5	365	1.78	Shear in key
	Sg-3	7.0	385	1.82	Shear in key
	Sg-4	6.5	365	1.78	Shear in key
3	Sg-4	6.5	365	1.78	Shear in key
	Sg-5	7.5	460	1.63	Crushing
	Sg-6	5.0	215	2.33	Shear in key
	Sg-7	4.0	180	2.28	Slipping
4	Sg-4	6.5	365	1.78	Shear in key
	Sg-8	7.5	220	3.41	Crushing
	Sg-9	8.0	415	1.93	Shear in key
5	Sg-7	4.0	180	2.28	Slipping
	Sg-10	4.0	140	2.85	Slipping

In order to study the effect of the tensile stress in strands on the ultimate load, test results show an increase in ultimate load capacity by about (69.8%) when the tensile stress in strands increased from (175MPa) to (524MPa). This may be due to increase in lateral force and as a result friction force between segments increased.

The use of epoxy increases the capacity of the specimens to carry the applied load by about (12.1%) compared to the load carried by the dry joint and this difference in strength can be explained by the fact that the dry key slipped while being tested, so that stresses were not distributed evenly in the epoxied keys. Consequently, there was a concentration of shear and compressive stresses at the lower face of the key. When the normal stresses increased, the frictional forces were higher resulting in less slip. Since less slip occurred, the stress concentration was not as prevalent along the lower face, and the joint acted more like a monolithic region.

To study the effect of joint type on the ultimate capacity, experimental results show that the ultimate load was increased from (365kN) (for dry joint specimen (Sg-4)) to (415 kN) (for epoxied glued joint specimen (Sg-9)) this is may be due to bonded joint using epoxy. The effect of specimen friction (specimens Sg-7) led to increase the ultimate capacity due to the increase in the bond between the parts of specimens. While, the effect of using grease between contact surfaces (specimens Sg-10) led to increases the displacement (slip) due to the increase in the slipping between the parts of specimens. Table (4) shows the first crack, ultimate load and mode of failure for all segmental specimens.

3-2- Crack Patterns

Crack patterns of tested specimens are shown in Figure (6). When the load is exerted on the segmental specimens, the first crack is formed at (1.6 to 3.4%) of the ultimate load for each specimens. The first crack appears at the zone of shear key. It was observed that the crack pattern is appeared in a certain manner for each group.

For the first group (Sg-1 and Sg-6), the first crack and other cracks takeplace within the shear key and increased in width and number (in vertical direction) as the applied load increased. The increase in pre-stressing level from(175MPa) to (524.2MPa) causes an increase in capacity of specimens to carrying the applied load by about (40%).

For the second group(Sg-2, Sg-3 and Sg-4), when the applied load is increased, the first crack and other subsequent cracks are increased in width and number. A decrease in crack width is noticed at shear key due to increasing of concrete strength. For fibrous concrete specimens(Sg-3), presence of steel fibers produced a slight increase in strength and ductility gains compared to the normal concrete specimen, eventhough the small ratio of steel fibers (0.75% by volume) are used, the specimens carried load by about (5.2%) more than normal concrete and the crack width is decreased at shear key due to effect of presence of steel fibers. Here, the steel fibers display the ability to control crack growth.

For the third group(Sg-4, Sg-5, Sg-6 and Sg-7), when the applied load is gradually increased, the none shear key specimen (Sg-7) has few cracks this may be due to absent of bond between the segments. In the other specimens of this group (Sg-4, Sg-5 and Sg-6), when the number of shear keys is increased, the cracks are decreased in number and width due to the increase in stiffness (bond) of specimens and as a result the load carying capacity of specimens was increased.For the fourth group (Sg-4, Sg-8 and Sg-9), the dry joints were significantly weaker than the epoxied joints. Final failure of both dry and epoxied joints was brittle, but the dry joints exhibited more cracking prior to failure. In specimen (Sg-8) the failure occurs in the body of the specimens and the load was carried by steel strands,see Figure (6).

Figure (6)-(A)- Crack Pattern of Tested Specimens

3-3- Load- Slip Relationship

Load versus slip (Displacement) curves for all tested segmental specimen are constructed and presented in Figures (7) to (11).

3-3-1- Group One

When the tensile stress is increased, it was found that ultimate load is also increased this is may be due to increase in stiffness of the segment and the friction at interface between segment components, Figure (7).

Figure (6)-(B)- Crack Pattern of Tested Specimens (Continue)

3-3-2- Group Two

In this group, it can be seen that effect of the type of concrete on the behavior of the segment, in specimen (Sg-2), an increase in the stiffness due to increase in strength of concrete is observed when compared with specimen (Sg-4), Also the presence of steel fibers in segmental specimen (Sg-3) increases the stiffness of the segment when compared with normal concrete segment, Figure (8).

3-3-3- Group Three

The increase in shear keys number led to decrease the slip; this may be due to the increase in stiffness of the segment and friction force (bond) between interface of segments, Figure (9).

3-3-4- Group Four

The effect of interaction between steel strands is clearly observed. When specimen without bond between steel strand and concrete (5cm space to unbound strand with concrete) has been used Figure (10), the failure in body of concrete due to the applied load is more than the strength of concrete (Sg-8). The presence of epoxy increases the strength capacity of the specimen due to increase in the cohesion between the segments and the crack occurred far away from shear keys when compared with the specimens without epoxy joint and having the same variables (Sg-4 and Sg-9).

3-3-5-Group Five

The effect of specimen friction increased the ultimate capacity due to increase in the bond between the parts of specimens. The effect of using grease between contact surfaces increases the displacement (slip) due to the increase in the slipping between the parts of specimens, Figure (11).

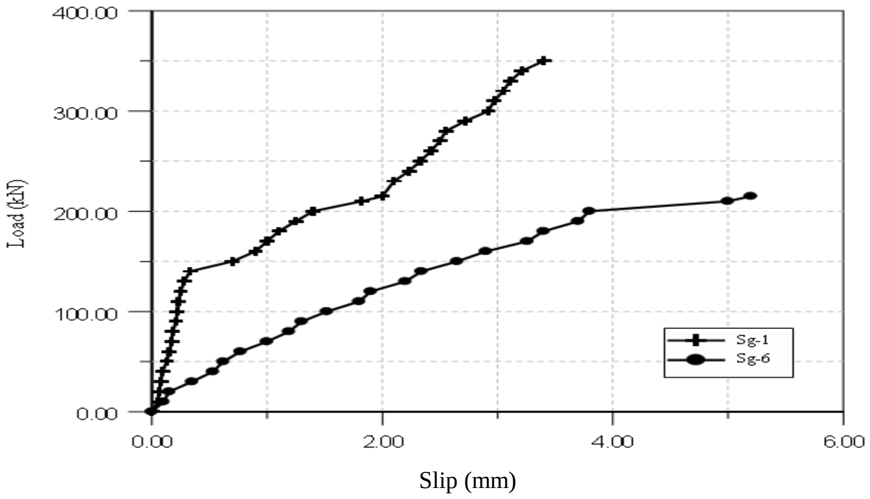

Figure (7) Load-Slip Curve for Group-1

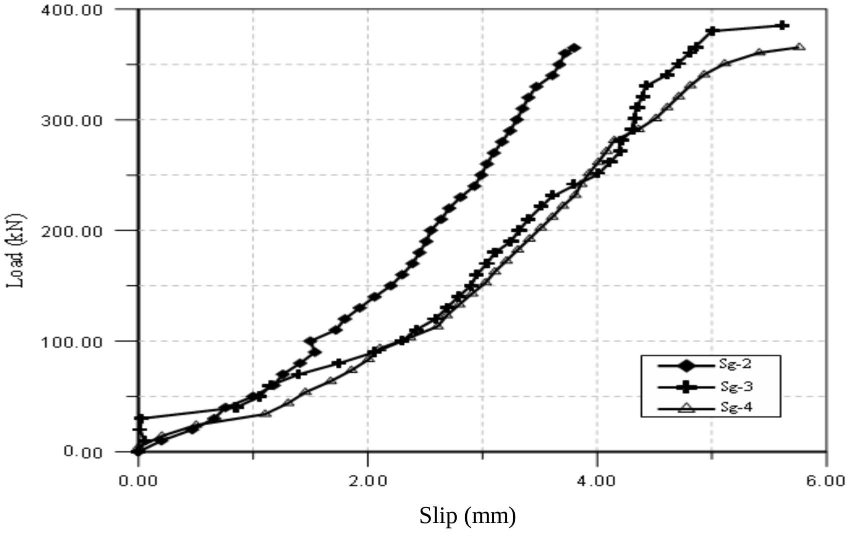

Figure (8) Load-Slip Curve for Group-2

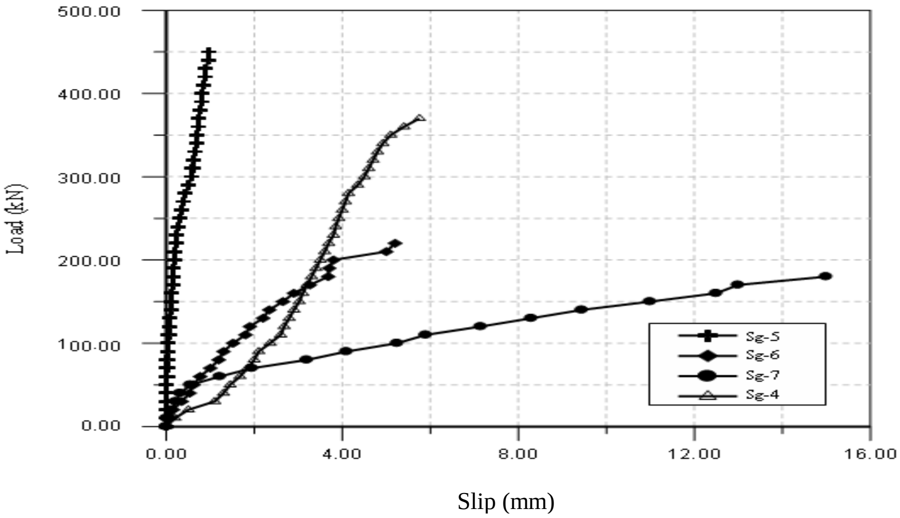

Figure (9) Load-Slip Curve for Group-3

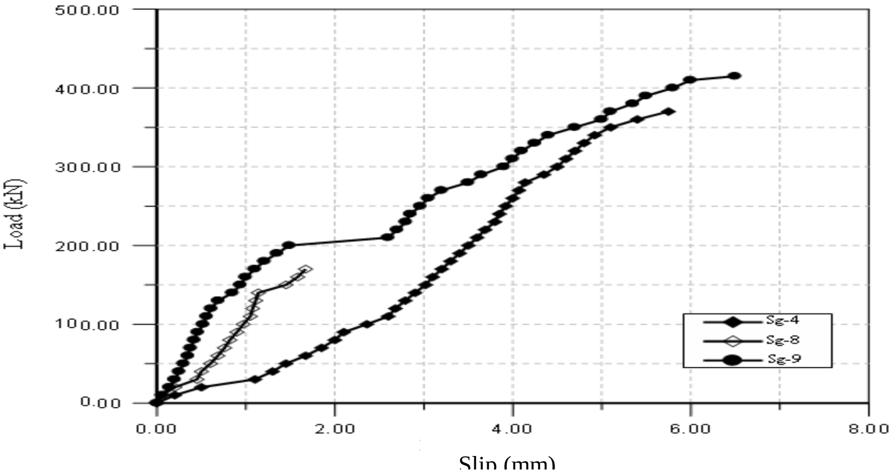

Figure (10) Load-Slip Curve for Group-4

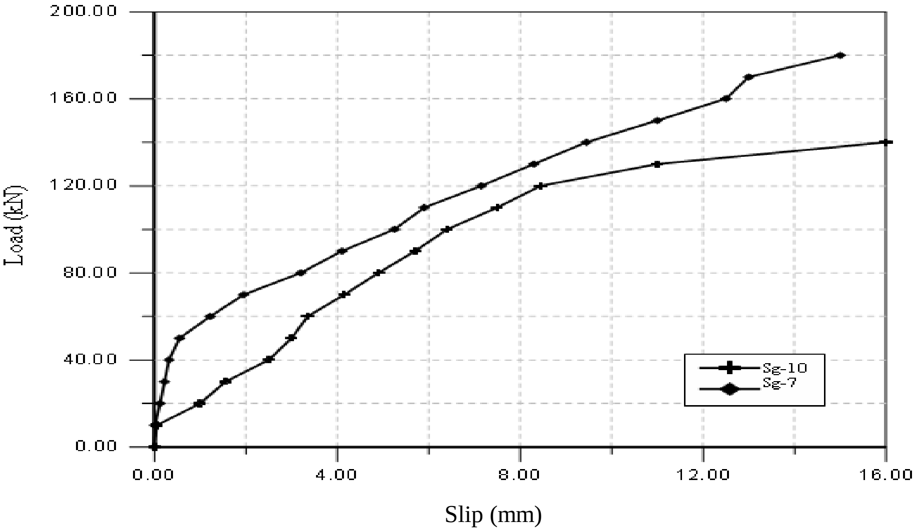

Figure (11) Load-Slip Curve for Group-5

3-4- Load–Lateral Displacement Relationship

In this part of the tests, the horizontal movement is measured at different load levels by using dial gauges (number 2 and 3) as shown in the Figures (2) and (12). In Figure (13), a comparison between the results obtained for specimens of the first group is made. It can be noticed that the amount of tensile stress in the steel strands affects the horizontal displacement, when the tensile stress in the strand increased, a decreased in horizontal displacement occurred, this is may be due to the increase in friction force and decrease in deformation due to strand relaxation.

Figure (12) Dial Gauges to Measure Lateral Movement

For the second group, Figure (14), the increase in the compressive strength leads to decrease in horizontal displacement due to increase in stiffness of specimen. For the third group, Figure

(15), the increased in the number of shear keys leads to decreases the horizontal displacement as results of increase in friction between segments. The friction delays the failure of the middle part of the specimens. For the fourth group, Figure (16), it can be seen that the interaction between steel strand and concrete decrease the horizontal displacement. Finally, Figure (17) shows the effect of using grazed joint (fifth group) between segments, causes an increase in the horizontal displacement.

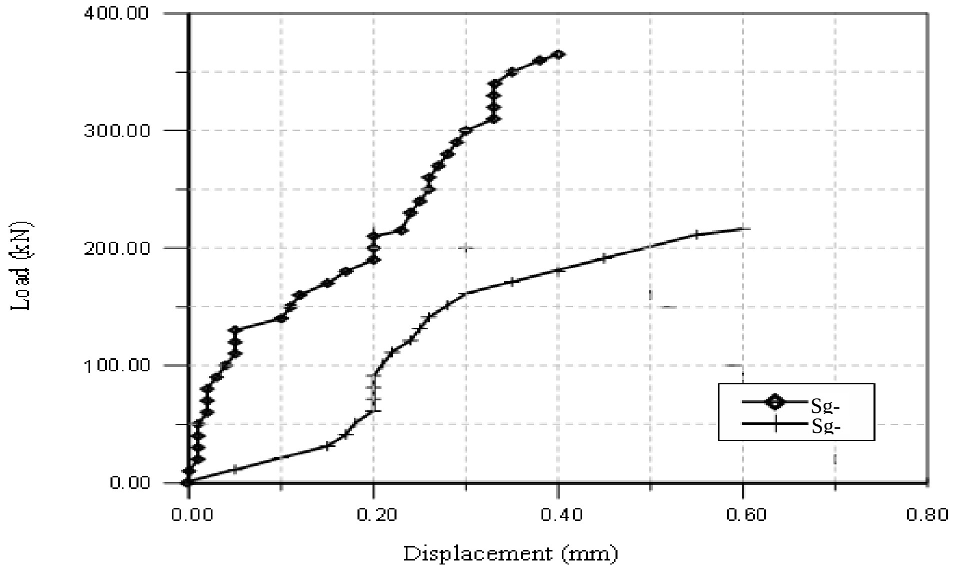

Figure (13) Load-lateral displacement for Group-1

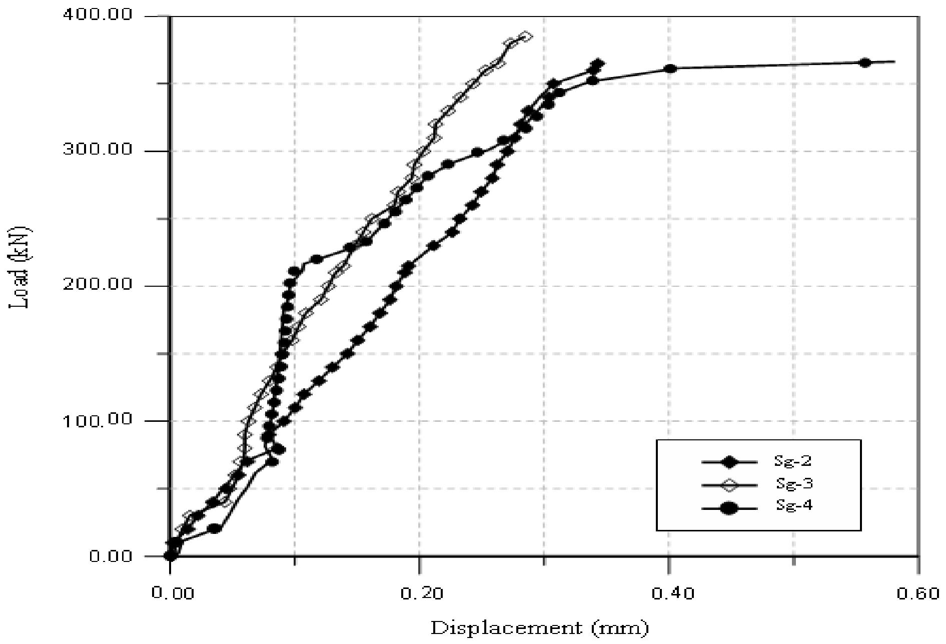

Figure (14) Load-lateral displacement for Group- 2

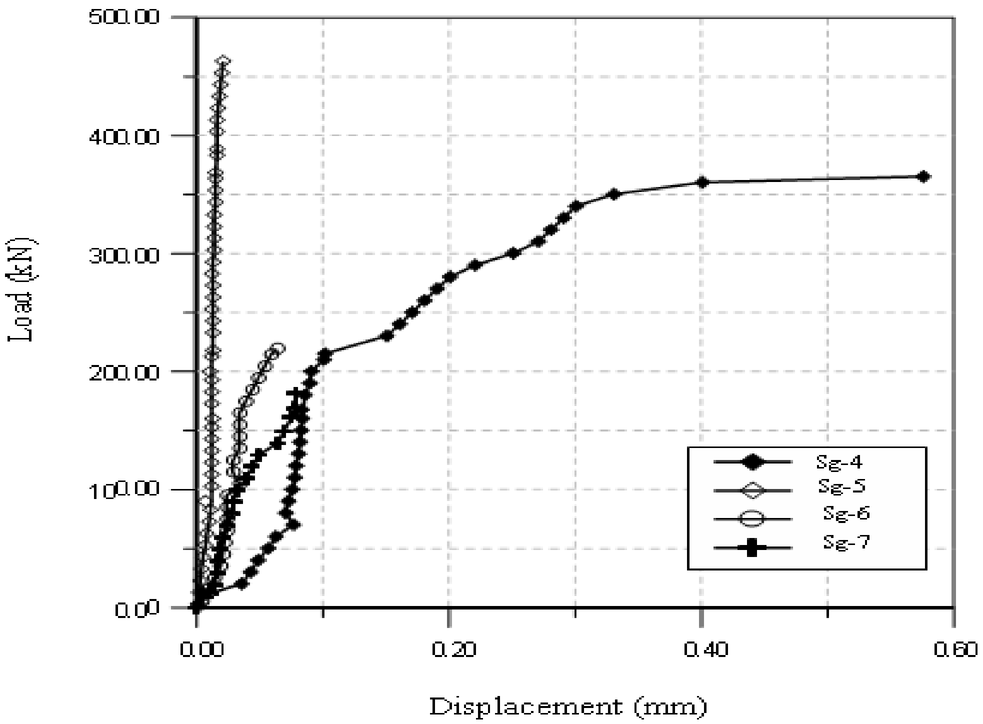

Figure (15) Load-lateral displacement for Group-3

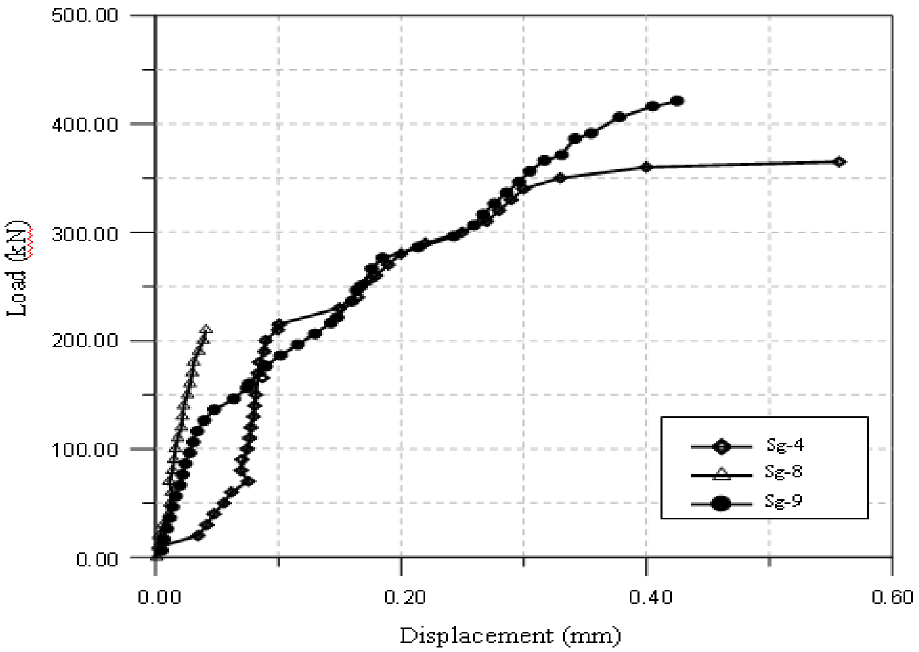

Figure (16) Load-lateral displacement for Group- 4

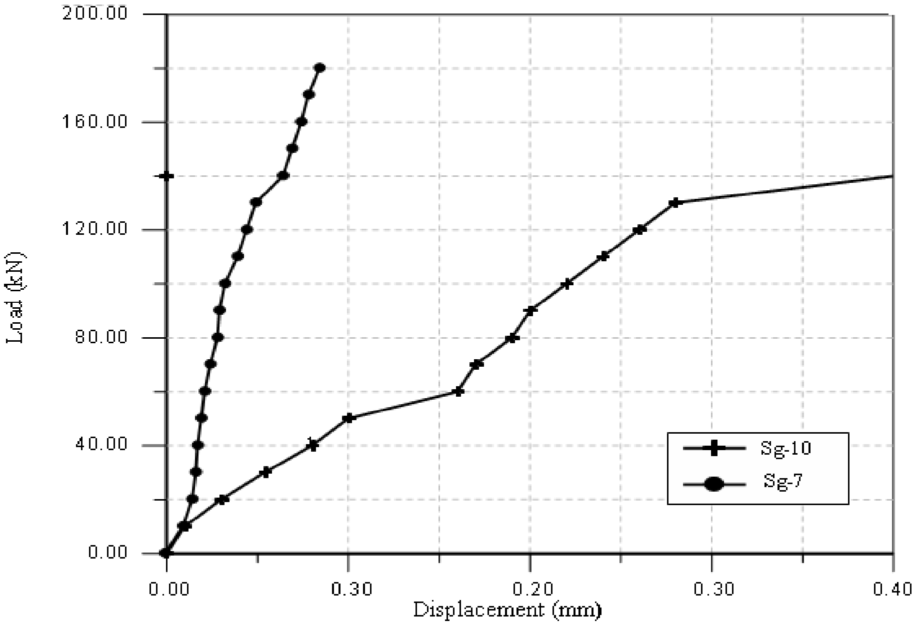

Figure (17) Load-lateral displacement for Group- 5

4- Conclusions

Depending on the test results of this study, the following conclusions are obtained:

1- The first crack load appears in the zone of the shear key, at a load level of (1.6 to 3.4 %) of the ultimate load of the segment when the applied load increased, the first crack and other subsequent cracks will increase in width, number and length until failure.

2- The ultimate load increased by about (16.27%),(50.68%) and (60.87 %) for specimens having (1),(2) and (3) shear keys respectively in comparison with ultimate load of reference specimen (without shear key).

3- When the prestressing force of the steel strand increased, from (175MPa) to (524.2 MPa), the deflection is reduced and the ultimate load increases by about (69.8%).

4- Interaction and presence of shear keys with prestressing strands at the interfaces between segments decrease the Slip of the segment specimen; this is be due to the increase in number of shear keys and prestressing compressive stresses.

5- The failure cracks occur in non-fibrous concrete specimens are very clear and wide, while such cracks are much finer and less in number in the specimens reinforced with steel fibers.

6- Epoxied joints of the specimens enabled the section to carry more load and increase the shear strength of the specimens. It was found that presence of epoxy increase the ultimate load by about (13.7 %).

7-The effect of specimen friction led to increase the ultimate capacity due to the increase in the bond between the parts of specimens. While, the effect of using grease between contact surfaces led to increases the displacement (slip) due to the increase in the slipping between the parts of specimens.

8- Since the contribution of the epoxy to the shear strength is significant as confirmed by this study and other studies, it is recommended that all formulas related to the shear keys (such as AASHTO formula) is required to be modified to take into consideration the effect of presence of the epoxy. This will significantly benefit the segmental bridge technology by producing a more secure and a finer crack joints.

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6-Notation

A_{ps}= Area of prestressing reinforcement;

E_c = Concrete modulus of elasticity;

E_s= Steel modulus of elasticity;

f_{ct} = Indirect tensile strength (splitting tensile strength);

f_c' = Cylinder compressive strength of concrete;

f_{cu}= Cube compressive strength of concrete;

f_r = Flexural tensile strength of concrete (modulus of rupture);

f_{pu} = Ultimate tensile strength of prestressing steel;

f_{py} = Yield tensile strength of prestressing steel;

f_y = Yield tensile strength of steel;

P_{cr} = Cracking load;

P_u = Ultimate load;

V_f= Volume fraction of steel fibers;

ϕ = Reinforced bar diameter