

# REVIEW ON SHEAR SLIP OF SHEAR KEYS IN BRIDGES

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## ABSTRACT:

The structural behaviour of precast concrete segmental bridges largely depends on the behaviour of the joints between segments. The current practice of precast concrete segmental bridges is to use small keys that are usually unreinforced, normally dry, and distributed over the height of the web and the flange of concrete segments. However, requires the presence of segmental joints to transfer the loads between neighbouring segments, which stresses the importance of securing structural safety and serviceability. Therefore, need is for research on the behaviour of the segmental joint for the structures erected by the precast segmental construction method. The work in this paper deals with the shear slip of the shear keys used in prestressed concrete segmental bridges due to the external load for which it is analysed using Finite element analysis and experimental works and the conclusion is given based on various results considerations.

**KEY WORDS:** shear key; displacements in shear key; segmental bridges; shear failure; precast concrete; FEM; bridges; joints.

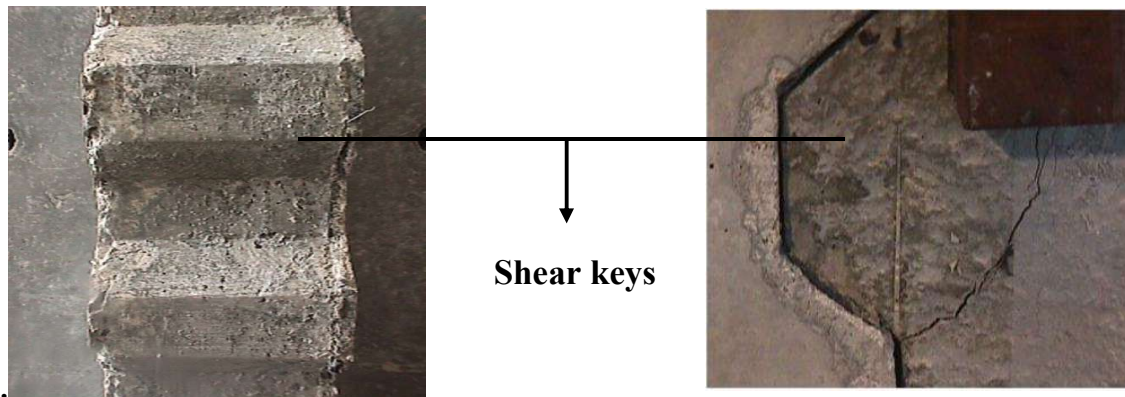
## INTRODUCTION:

Precast concrete segmental box girder bridges externally prestressed have become more and more popular in construction resulting from the demand for economical and safe design; fast, versatile, and practical construction; and excellent serviceability of concrete bridges (**Poston and Wouter 1998**). 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 behaviour, including the ultimate strength of segmental bridges, depends on the behaviour 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 (**Ihsan etal 2012**). Also by implementing shear keys throughout the web and flange for interlocking performance and external prestressed to form a superstructure. These shear joints can be of dry or can be fixed with a epoxy layer developed essentially the same strength as monolithic specimens.

## SHEAR KEY:

The shear key 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 (**Ihsan etal 2012**). The first mechanism depends on the friction resistance between the flat surfaces, which attempt to slide against each other. This resistance is proportional to the actuating compression load, i.e., the confining pressure. The second

mechanism represents the support effect of the castellated shear keys, which behave like small plain concrete corbels when they are in contact. (Rabee Shamass et al 2014)



### SHEAR STRENGTH OF KEYED JOINTS:

The AASHTO formulation (AASHTO 1999) for shear strength of keyed joints is as follows:

$$V = A_k \sqrt{6.792 \times 10^{-3} f_{cm}} (12 + 2.466 \sigma_n) + \mu \cdot A_{sm} \cdot \sigma_n \quad (1)$$

Where

$A_k$  = area of the base of all keys in the failure plane.

$f_{cm}$  = characteristic compressive strength of concrete (MPa).

$\sigma_n$  = average compressive stress in concrete across the key base area (MPa).

$\mu$  = friction coefficient between concrete-to-concrete surfaces.

(0.6 suggestion by AASHTO)

$A_{sm}$  = area of contact between flat surfaces on the failure plane.

### STUDIES CARRIED ON SHEAR KEY:

**Buyukozturk et al. 1990:** made tests to assess the shear strength and deformation behaviour of precast segmental bridge joints. The parameters studied included flat and keyed joints, without epoxy (dry) and with, the level of prestressing, and the epoxy thickness. It was found that the strength of epoxied joints was consistently higher than that of dry joints. However, the failure of the epoxied joints were found to be very sudden and brittle. Formulas are proposed for assessing the shear strength of PCSB joints. Combinations of these formulas with the current ACI and AASHTO specifications for shear design, aimed at preventing diagonal failures, may provide a rational basis for the design of PCSB. For the keyed specimens, a general specimen layout similar to that of the flat joints was used, as shown in Fig. 1.

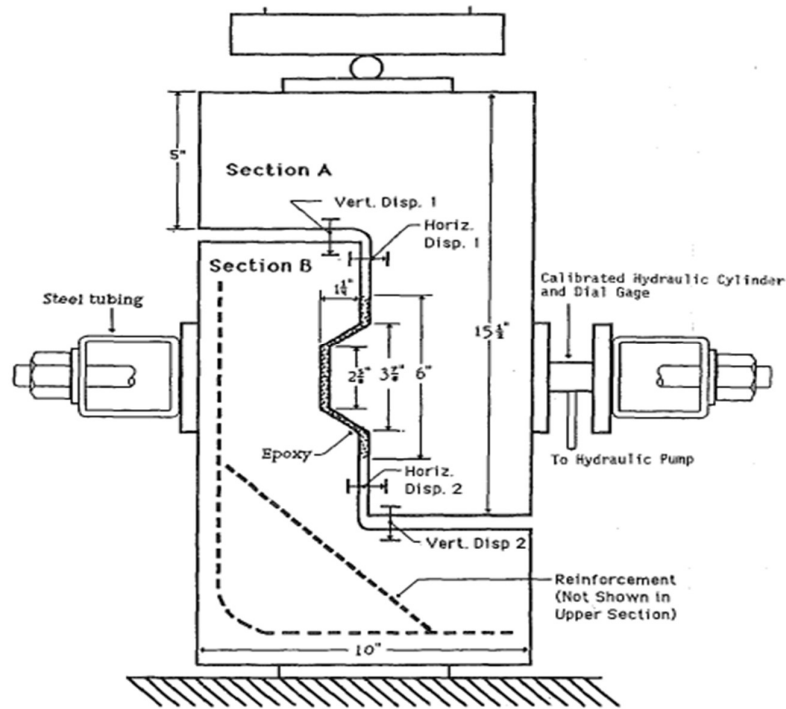


Fig 1 Test setup for keyed specimen

The specimen was enlarged to accommodate the shear key and to ensure that a sufficient amount of concrete was available below the key to prevent any premature failure of the specimen. The specimens were reinforced with two bent # 5 bars and two straight # 3 bars as shown in Fig. 1.

**Rabee Shamass et al 2014** carried out parametric studies on structural behaviour of keyed dry joints using numerical simulation. They recommended for the modification of AASHTO's formula Eq. (1) for shear capacity of keyed dry joints. a linear elastic and fully plastic bilinear stress-strain material model was used for reinforcement bar in tension and compression. The yield strength  $f_y$ , elastic modulus  $E_s$ , and Poisson's ratio  $n$  of reinforcement bar were taken as 400 MPa, 210 GPa, and 0.33, respectively. The single-keyed dry joints were also analysed and tested by Zhou et al. (2005) and Buyukozturk et al. (1990) using FE code ABAQUS, based on the model parameters discussed previously. In Zhou's specimens, the overall dimensions of the single-keyed dry joints were 500 x 620 x 250 mm<sup>3</sup> with 250 mm as the thickness of the joint including a male part and a female part (Fig. 6). The castellated joint had a 100 x 250 mm<sup>2</sup> base area and a 50 x 250 mm<sup>2</sup> top area with a 50-mm depth. The most critical area in which cracking happens was the castellated keyed area, where a finer mesh with nominal element size of approximately 5 mm was used, compared with a coarser mesh, with the nominal element size of approximately 15 mm that was used for the rest of the model. Four-node bilinear plane stress quadrilateral elements (CPS4) were used for modelling the key assembly. The plane stress thickness was taken as 250 mm. There were, in total, 2,255 elements for a typical single-keyed dry joint assembly.

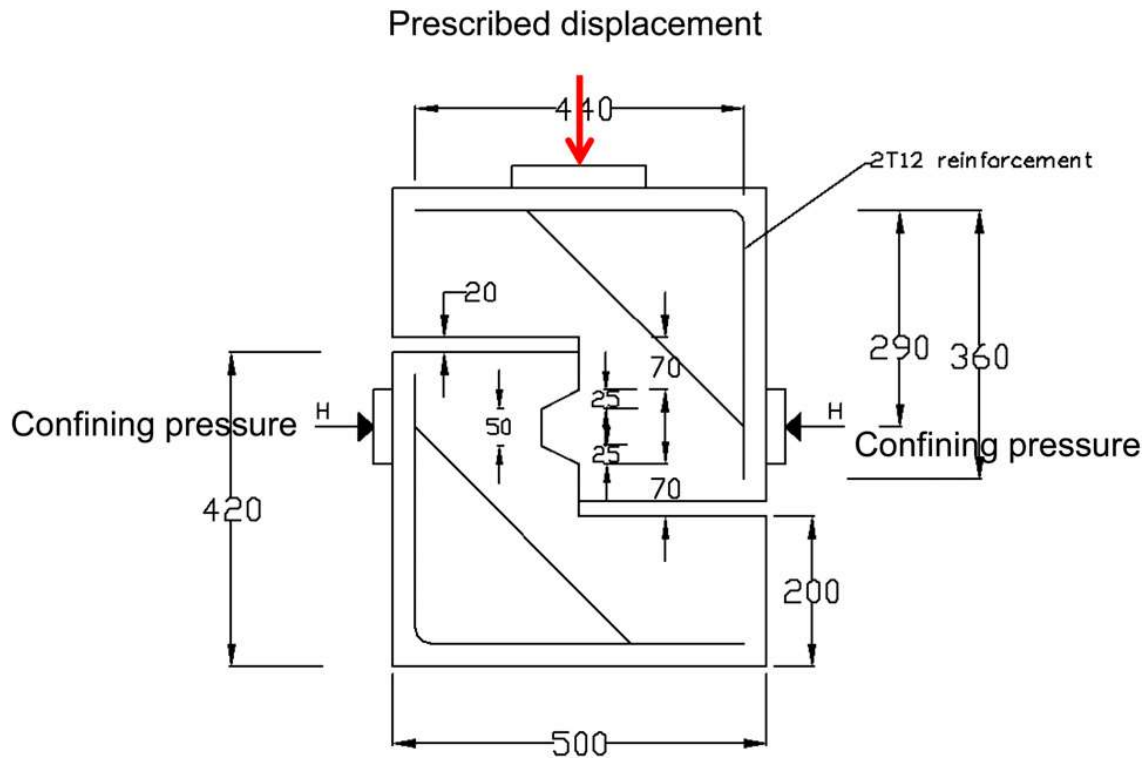


Fig 6 Dimensions of the single-keyed joints tested by Zhou et al. (2005)

A full integration algorithm was used in numerical analyses. For those keyed joints tested by Zhou et al. (2005), the specimen identifier was represented as Mi-D-Km-n,

where M = monotonic loading

i = confining stress in mega pascals,

D = dry joint,

K = keyed joint,

m = key number,

n = test number under the same testing condition.

## RESULT & DISCUSSION:

The analytical values of the ultimate loads/shear strength of nine single-keyed dry joints are summarized in Table 1, along with the corresponding experimental values reported by Zhou et al. (2005) and Buyukozturk et al. (1990).

Table 1 comparison of experimental and numerical strength

Test name	$f_{cm}$ (Mpa)	Experimental ultimate strength (kN)	Numerical ultimate strength (kN)	$v_{u(numerical)}/v_{u(experimental)}$
M1-D-K1-1	38.7	193	180.8	0.94
M1-D-K1-2	50.0	211	219.1	1.04
M2-D-K1-1	56.2	335	294	0.88
M2-D-K1-2	59.6	337	314	0.93
M3-D-K1-1	80.1	448	429	0.96
M3-D-K1-2	48.8	360	324	0.90
M4-D-K1-1	37.1	354	312	0.88
M4-D-K1-2	36.7	392	309	0.79
M4-5-D-K1-1	37.7	375	332	0.89
Keyed Dry 0.69 MPa	48.4	66	59	0.9
Keyed Dry 2.07 MPa	47.6	84	78	0.93
Keyed Dry 3.45 MPa	49.44	111	99	0.89
Average				0.91

The predicted ultimate shear strength for joints were all in good agreement with the corresponding experimental results. The average deviation was approximately 9%. It appears that the model used in the analysis was reliable and it was generally conservative in predicting the ultimate shear strength of a single-keyed dry joint. Figs. 7 and 8 show numerical results of the applied load versus the deflection at the top surface of the joint. There is an obvious drop in loading at ultimate strength in all the load-displacement curves obtained from numerical simulation, which is associated with shear off failure of the key. Also, a higher concrete strength led to higher ultimate shear strength of the joint. After shear off failure of the keys, residual strength was kept, owing to friction between cracked concrete surfaces under confinement. The residual strength of a joint largely depends on the confining pressure (Fig. 7).

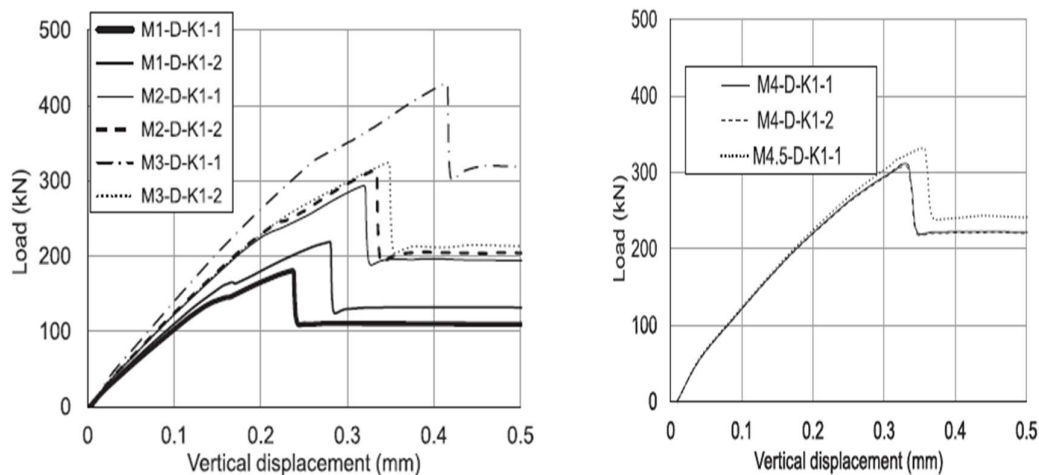


Fig 7 Load-displacement curves from numerical analysis for keyed dry joints of Zhou et al. (2005)

As confining pressure increased from 1 to 4.5 MPa, the residual strength generally increased; but, it also depends on concrete strength. M3-D-K1-1 demonstrated the highest residual strength owing to the highest concrete strength (80.1 MPa) of the nine single-keyed dry joints tested by Zhou et al. (2005). Also apparent from Fig. 8, the initial stiffness increased with the increase of confining pressure, and the vertical deformation of the joint at peak load increased as confining pressure increased. For those single-keyed dry joints tested by Buyukozturk et al. (1990), these findings are more obvious as the concrete for making the three keyed joints was the same grade of concrete. Both ultimate shear strength and residual strength of keyed dry joint increased as confining pressure increased (Fig. 8).

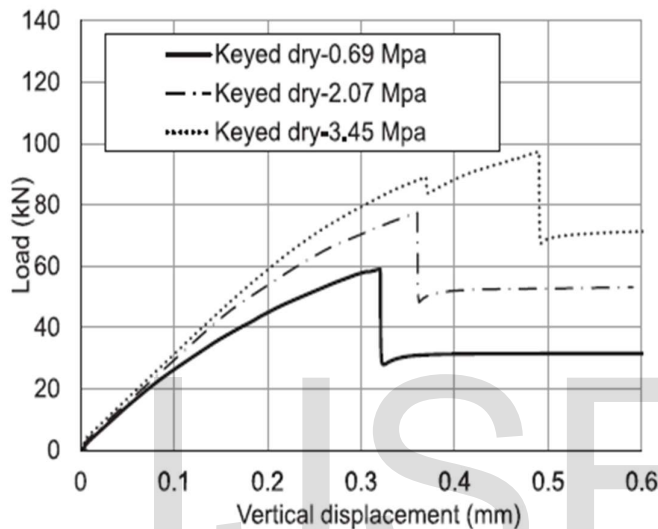


Fig 8 Load-displacement curves from numerical analysis for keyed dry joints of Buyukozturk et al. (1990)

Again, initial stiffness and vertical deformation of the joint at peak load increased as confining pressure increased.

Numerous points on the FE-predicted load-displacement curve in Fig. 9(a) for the specimen M1-D-K1-2, Fig. 10(a) for the specimen M3-D-K1-1, and Fig. 11(a) for the specimen Keyed Dry-2.07 MPa were chosen to interpret crack initiation and the propagation process. All these figures obtained from numerical analyses from various specimens indicated similar crack evolution and ultimate shear-off failure. The distribution of diagonal cracks along the root key increased and formed multiple cracks. That indicates all the concrete fibres at the base key were cracked and the compression struts between multiple diagonal cracks exposed to crushing [Figs. 9(b), 10(b), and 11(b)], which coincides well with the experimental observation that there was concrete in the surface of keyed area spalling (Zhou et al. 2005). On the other hand, the experiments revealed the formation of the diagonal multiple cracks along the root of the key, which eventually separated the key from the male part resulting in the so-called shear off failure. The reason why numerical results showed a sudden decrease in the load-deflection curve could be because all the concrete fibres along the root of the key were cracked and crushed simultaneously, owing to the same material properties being assumed for the whole concrete volume. However, experimental observations do not show a sudden drop in load, because a direct failure plane formed along the joint surface and the load then was carried mainly through friction by aggregate interlock between cracked concrete surfaces, which is not able to be simulated by the FE model developed in this study.

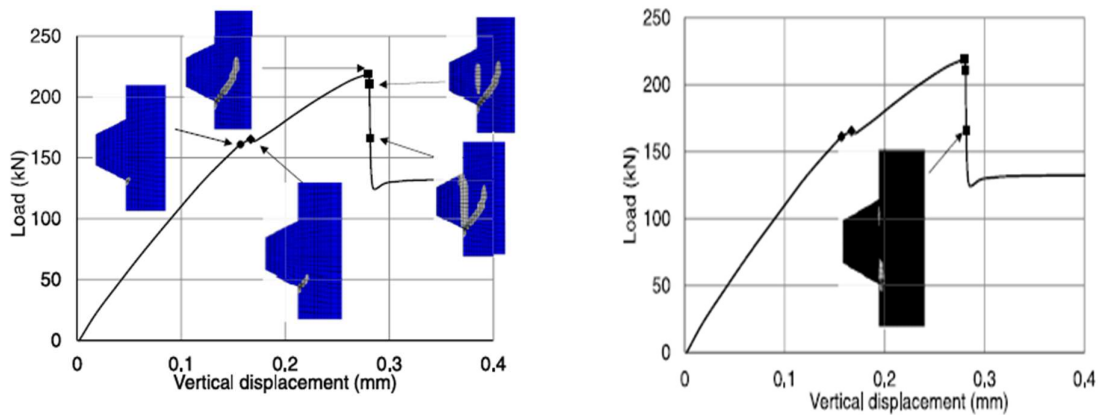


Fig 9 (a) Crack patterns of specimen M1-D-K1-2; (b) concrete crushing evolution on the root of the key specimen M1-D-K1-2

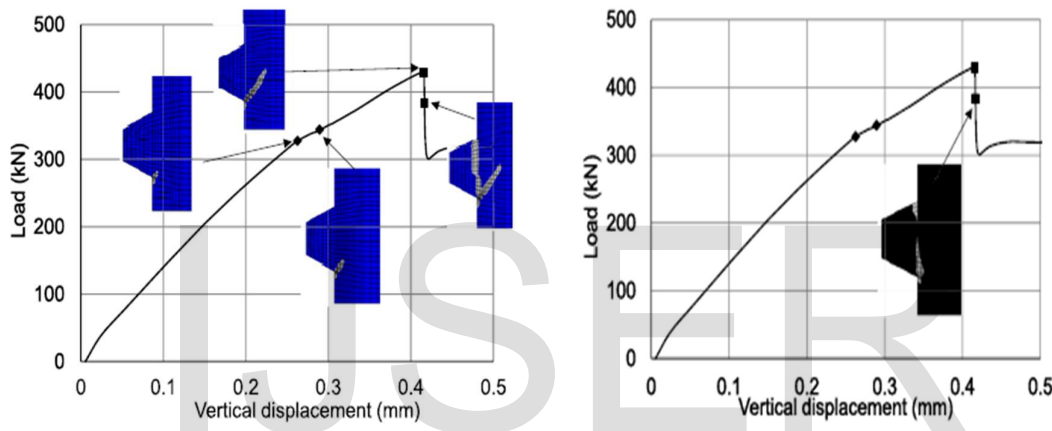


Fig 10 (a) Crack patterns of specimen M3-D-K1-1; (b) concrete crushing evolution on the root of the key specimen M3-D-K1-1

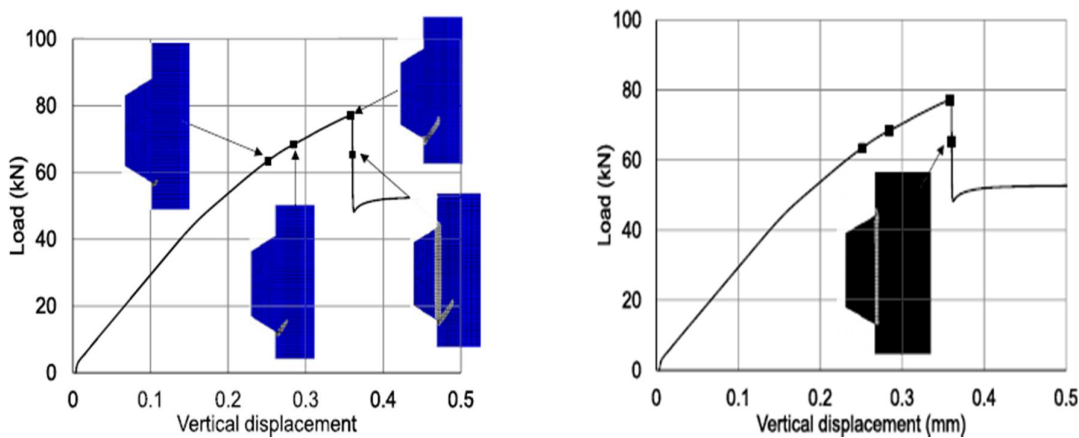


Fig 11 (a) Crack patterns of specimen Keyed Dry-2.07 MPa; (b) concrete crushing evolution on the root of the key specimen Keyed Dry-2.07 MPa

Figs. 10(a and b) show the crack patterns for the specimen M1-DK1-2 associated with tension strains of  $\epsilon_0$  or higher and concrete crushing associated with compression strain 0.0035 or higher at the applied loads of 161, 165, 219, 211, and 166 kN, which correspond to the applied displacements of 0.157, 0.167, 0.28, 0.281, and 0.282 mm, respectively. Additionally, Figs.

10(a and b) present the crack patterns and crush evolution of the specimen M3-D-K1-1 at the applied loads of 328, 344, 429, and 383 kN, which correspond to the applied displacements of 0.266, 0.289, 0.415, and 0.416 mm, respectively. Moreover, Figs. 11(a and b) show the crack patterns and crush evolution of the specimen Keyed Dry-2.07 MPa at the applied loads of 63, 68, 78, and 65 kN, which correspond to the applied displacements of 0.251, 0.284, 0.358, and 0.360 mm, respectively. From these predicted crack evolution histories, one can see that basically cracking initiates at the bottom corner of a key and propagates sideways and upward at approximately  $45^\circ$  to the horizontal; then this crack ceases to grow. Later on, vertical cracking, which is a new crack, initiates from the bottom of the key and propagates upward vertically in the loading plane. It is this crack initiated later that causes the ultimate shear-off failure of the key from its base when it propagates to the top corner of the key.

**Ihsan et al 2012:** Investigated the effect of types of joint (dry, epoxy), number of shear keys and type of concrete used on the behaviour and load carrying capacity of reinforced concrete segmental specimens. 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 (12). The segmental specimens were divided into five groups as shown in Tables (2) and (3).

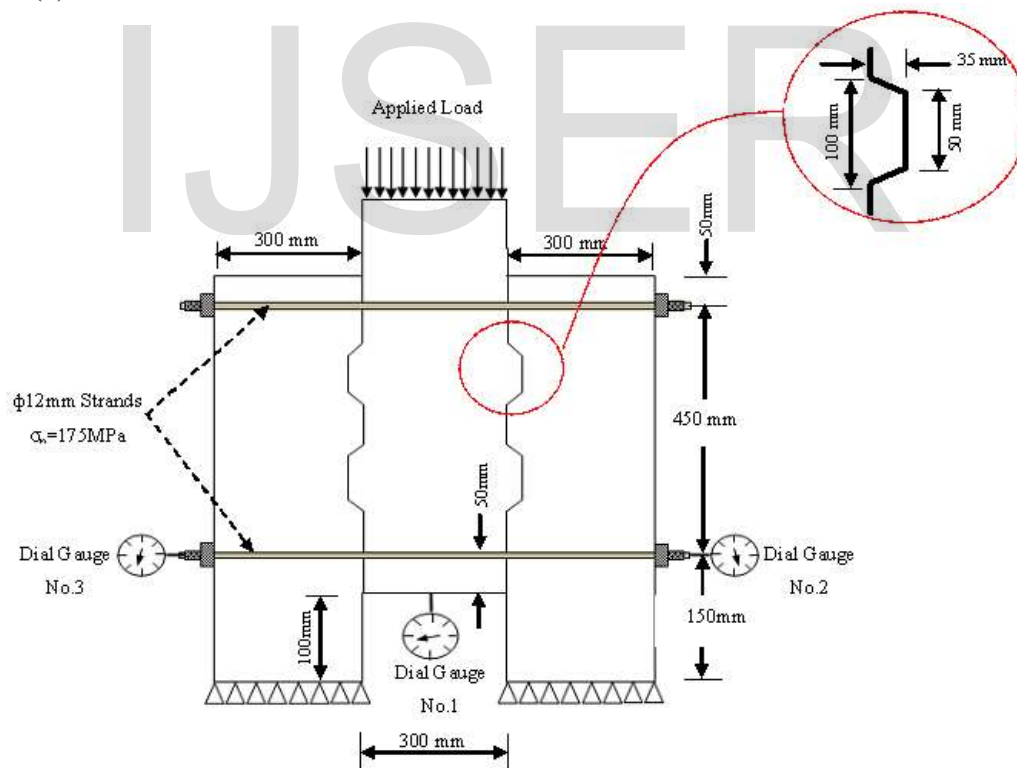


Fig 12 Details of Segmental Specimens



Table 2 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 3 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

The prestressing force in cables were given by using Hydraulic Machine. During the test, the applied load, the corresponding slip and lateral movement between segmental specimens are measured using the universal testing machine and dial gauges for measuring vertical and horizontal displacements, then the readings from each tested segmental specimens are collected and used to draw load-Slip curves. All tests are carried out initially under the condition of load control of 5kN increments, and then reached to the ultimate load.

**Group 1:** It was found that ultimate load increased with increase in stiffness of the segment and the friction at interface between segment components, Figure 13.

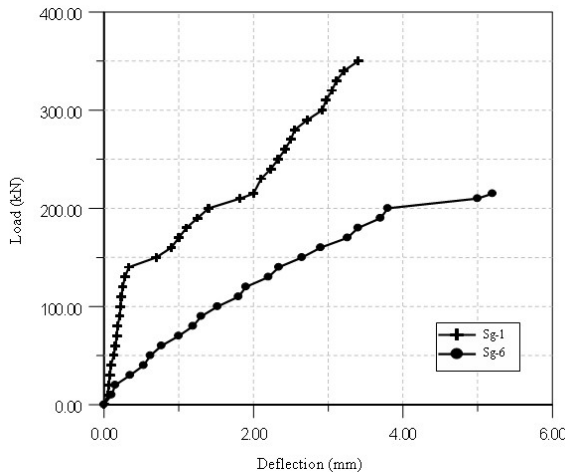


Fig 13 displacement curve for group 1

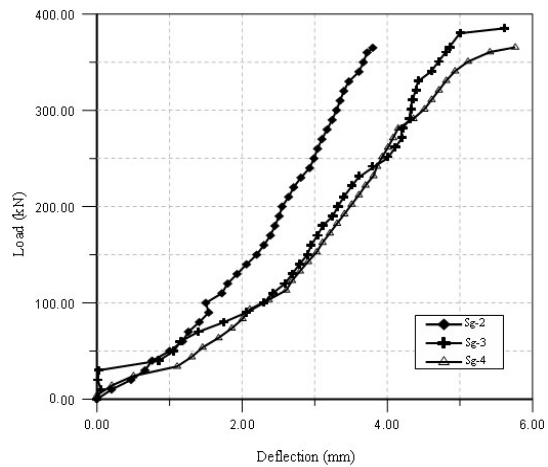


Fig 14 displacement curve for group 2

**Group 2:** In this group, it can be seen that effect of the type of concrete on the behaviour 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 fibres in segmental specimen (Sg-3) increases the stiffness of the segment when compared with normal concrete segment, Figure 14.

**Group 3:** 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 15.

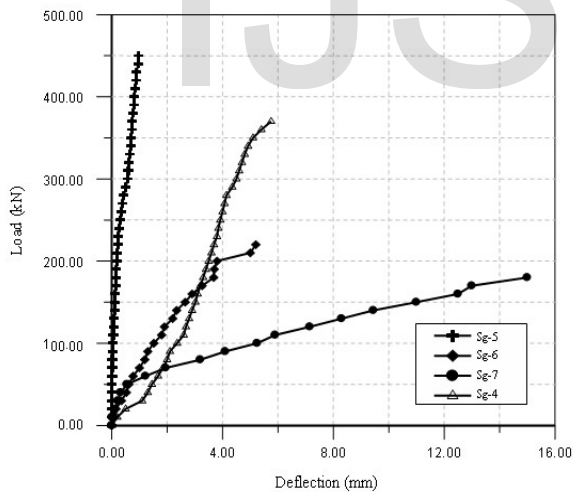


Fig 15 displacement curve for group 3

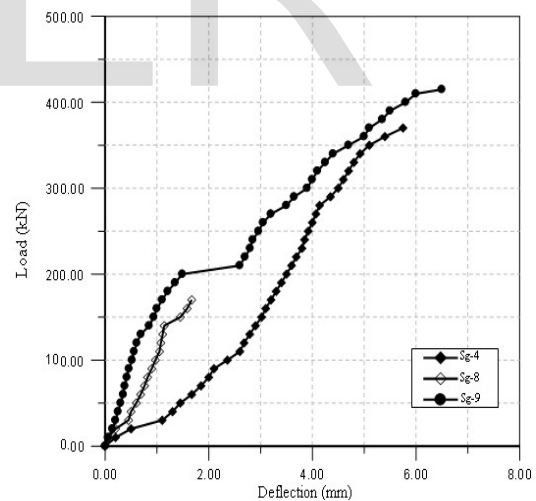


Fig 16 displacement curve for group 4

**Group 4:** When specimen without bond between steel strand and concrete (5cm space to unbound strand with concrete) has been used Figure 16, 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).

**Group 5:** 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 17.

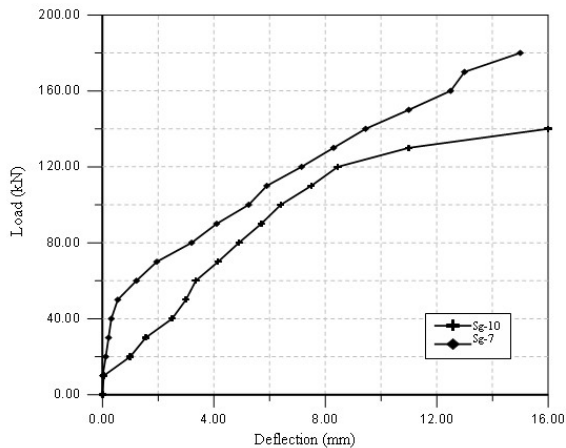


Fig 17 displacement curve for group 5

## CONCLUSION:

Based on the experimental and finite element analysis, the following considerations are clear

- The shear strength of the shear keys increases with the certain increase in confining pressure.
- 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 fibres.
- The crack pattern obtained numerically revealed that the crack, which is called S crack, first formed at the bottom corner of the key of the male part of a joint at approximately 72–80% of the ultimate shear strength and propagated sideways and upward from the base key at almost  $45^{\circ}$ , which is coincident with experimental observations.
- The ultimate shear strength obtained using the AASHTO formula of keyed dry joints under low values of confining stress well when compared with numerical results. However, it over predicts the ultimate shear strength of keyed dry joints under high confining stress.
- The joint which are layered using epoxy are capable of carrying more load than the dry joints i.e., it increases the ultimate load by 13.7%.

Based on the results it is proposed that the 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. The load could also be used as a confining pressure over the shear key by making it horizontally and it could also resist displacement laterally by proper location and design. This will significantly benefit the segmental bridge technology by producing a more secure and a finer crack joints.

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