BEHAVIOUR OF IN-SITU CONCRETE STITCHES IN SEGMENTAL PRESTRESSED CONCRETE BRIDGES

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ABSTRACT

The in-situ concrete stitches of a segmental prestressed concrete bridge are locations of potential weakness for the entire bridge deck but relatively little work has been carried out in this area. In the current practice, these in-situ stitches are usually designed to be capable of sustaining considerable sagging moment but only minimal hogging moment. Therefore, failure of these joints is possible under exceptional circumstances when the hogging moment is high, which may potentially trigger a progressive collapse. In the light of this, an extensive experimental study on the structural behaviour of the in-situ concrete stitch under different combinations of parameters has been carried out. Two types of specimens are tested in the study, namely the beam specimens and the shear specimens, which both consist of two precast units joined together by in-situ concrete stitch of variable widths. The beam specimens are internally prestressed and subject to different combinations of bending moment, shear, and prestressing force; while the shear specimens are either internally or externally prestressed and subject to direct shear only. Shear keys are provided to the stitch of several shear specimens to examine the contribution of the keys to the shear strength. The effects of various parameters on the strength of the stitch and ductility of the specimens are investigated. Detailed coverage on the experimental programme and the results of the experimental analyses are presented in this paper.

KEYWORDS

Experimental study, joints, prestressed concrete, segmental bridges, in-situ stitches.

INTRODUCTION

Precast segmental concrete bridges have gained popularity over the past 40 years due to their efficiency in coping with difficult site conditions. One of the most commonly used method of constructing this type of bridges is the balanced cantilever method, which essentially involves sequentially extending precast segments outwards from each pier in a balanced manner. A gap of 100 to 200 mm in width is usually provided around the mid-span location between the last two approaching segments to facilitate erection. In-situ concrete is then cast to 'stitch' the segments together, thus making the bridge deck continuous.

Under the current practice, the in-situ concrete stitches are usually designed to be capable of sustaining considerable sagging moment but its hogging moment capacity and shear resistance are only nominal. Failure of these joints can only occur under exceptional scenarios when hogging moment is high. However if it really occurs, this could potentially trigger a progressive collapse mechanism because the concrete stitches are locations of potential weakness. Studies on the joints of segmental bridges have been conducted in the past (Buyukozturk *et al.*, 1990; Hewson, 1992; Zhou *et al.*, 2005; Issa and Abdalla, 2007) but the joints studied are either dry or epoxy joints that exists between precast segments and not the in-situ concrete stitching joint that is of interest. As relatively little research work on this area has been conducted, understanding of the actual behaviour of in-situ stitches is limited.

In the light of this, an extensive experimental study has been carried out to investigate the behaviour of the in-situ concrete stitches. The study mainly involves a series of loading test on specimens that are comprised of precast units connected by in-situ concrete stitches. The stitch is subjected to different combinations of internal forces by applying loading at different locations along the specimen. Various parameters of the specimens are varied to examine their effect on the strength of the in-situ stitch and its failure mode. These parameters include the width of the stitch, the grade of concrete, the prestressing force, the provision of shear keys, the type of tendon (bonded or unbonded) and the type of prestressing (external or internal). Although the experimental programme is still ongoing, based on the analysis of the current experimental results, several preliminary conclusions have been drawn and are presented in this paper. The experimental programme is also covered in detail in this paper.

TESTING PROGRAMME

The experimental study involves load testing on two types of specimens, namely (i) the beam specimens, and (ii) the shear specimens. The beam specimens are used to study the behaviour of the in-situ concrete stitches subjected to different combinations of bending moment and shear, while the shear specimens are used to study the behaviour of the stitches under direct shear. Both the beam and shear specimens consist of two precast units joined together by the in-situ concrete stitches. Control beam specimens have also been fabricated where the entire beam is continuously cast without any stitch along the beam. Typically, the stitch is cast one week after the casting of the precast units. Loading test on the specimens is performed using a testing frame after 28 days from the day of casting of the stitch. Linear variable displacement transducers (LVDTs) are mounted on the specimens at various locations of interest to measure the displacements at these locations.

Configuration of the Beam Specimens

The length of the beam specimen is 1400 mm with the in-situ concrete stitch at either the mid-span of the beam or offset from the mid-span depending on the internal force that the stitch is subjected to. An actual beam specimen is illustrated in Figure 1. Three cases of internal force at the stitch are examined, namely (i) pure bending moment, (ii) pure shear, and (iii) both moment and shear. The loading test setup to induce the three cases of internal force condition is illustrated in Figure 2.

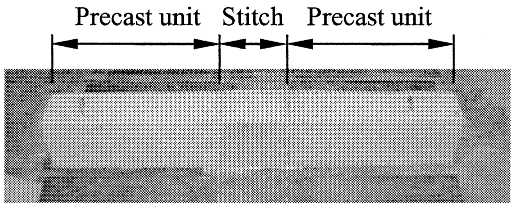
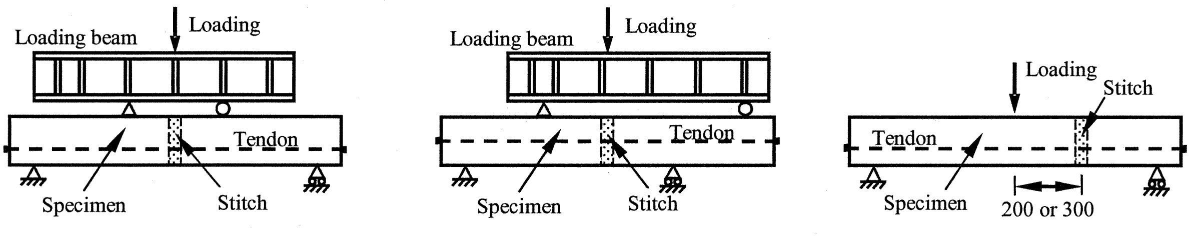


Figure 1. The beam specimen



(a) Case of pure bending moment (b) Case of pure shear (c) Case of moment and shear

Figure 2 Loading setup for beam specimens

The section of the beam has an overall depth of 200 mm and a width of 150 mm. A 7-wire steel strand with a nominal area of 100 mm^2 is used as the prestressing tendon. The tendon is placed at a depth of 133 mm for Case (i) and Case (ii), and 100 mm for Case (iii). For all beam specimens, Grade 60 concrete is used for both the precast units and the stitch. No shear key is provided to the stitch. Unbonded tendon with an effective prestressing force of 100 kN is applied to all beam specimens.

Since the precast units and the in-situ concrete stitch are cast at different time, construction joints exist in the specimen. Prior to casting the in-situ concrete stitch, the laitance at the construction joint area on the surface of the precast unit is removed and the area is roughened by a needle gun until the aggregates are exposed. The construction joint is then wetted for at least 12 hours before casting by laying towels that are completely saturated with water over the joint area.

Configuration of the Shear Specimens

The shear specimens consist of two L-shaped precast units with the in-situ concrete stitch joining the two units as illustrated in Figure 3. The out-of-plane dimension of the specimen is 200 mm. The specimens are either made of Grade 60 or Grade 45 concrete and both the precast units and the stitch are made of the same grade of concrete. The stitch is subject to a prestress of either 1 MPa or 5 MPa, and stitch widths of 100 mm and 200 mm are examined.

The shear specimens are designed in such a way that they are capable of simulating the shear behaviour of box girders of different web configurations. The web of a box girder may or may not be provided with shear keys and some parts of the web may or may not have prestressing tendon running through. Therefore, the specimens are either internally prestressed by bonded tendon or externally prestressed by a clamping device to provide the prestressing force acting on the stitch, while the stitch is either plain or provided with shear keys. For those specimens with shear keys, either one large key with a depth of 50 mm or two smaller keys with a depth of 30 mm are provided. Examples of an externally prestressed specimen with two shear keys and an internally prestressed specimen without shear key are illustrated in Figures 3(a) and 3(b) respectively. For the case where the specimen is internally prestressed, a 7-wire steel strand is used.

Prior to casting of the stitch, light roughening is provided at the construction joint area on the precast units to remove the laitance. Similar to the beam specimens, the joint area is wetted for at least 12 hours before casting the stitch.

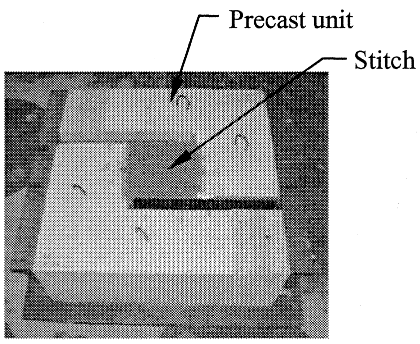
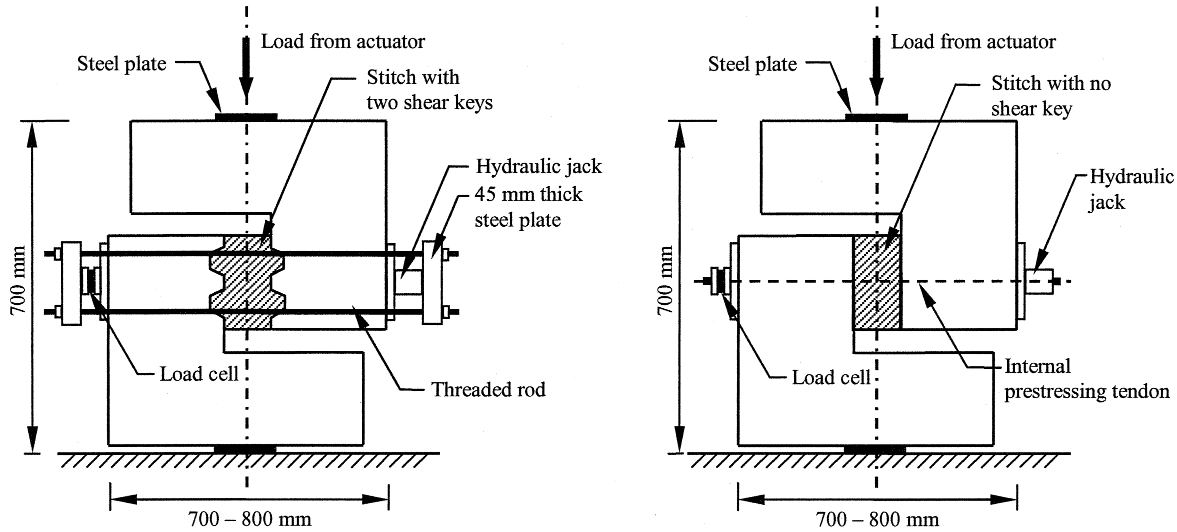


Figure 3 The shear specimen



(a) Stitch with shear keys; externally prestressed (b) Stitch without shear key; internally prestressed

Figure 4 Examples of setup for shear specimen

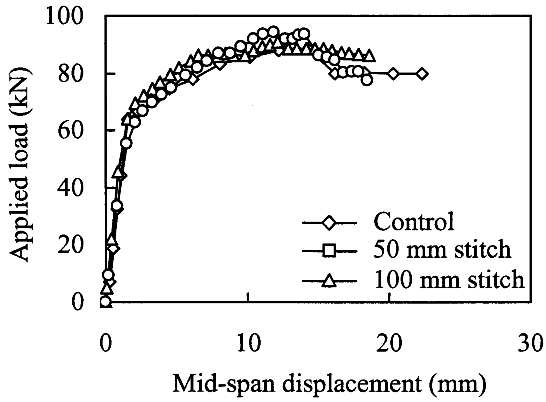
RESULTS AND DISCUSSION

Beam Specimens

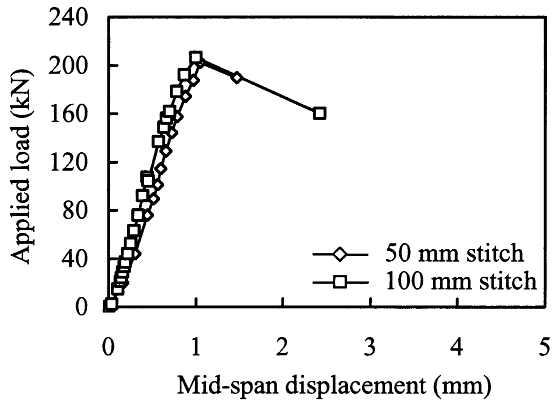
The load-displacement relationships of the beam specimens tested are plotted in Figures 5(a), 5(b) and 5(c) for the case of the in-situ concrete stitch subjected to pure bending moment (Case (i)), pure shear (Case (ii)), and a combination of moment and shear (Case (iii)), respectively. For the specimens of Cases (b) and (c), only the results of the specimens with 50 mm stitch and 100 mm stitch are available to date.

Ductile behaviour is observed for the beam specimens of Case (i). Opening of the construction joints occurs at a load of between 70 kN and 80 kN, while the final mode of failure is concrete crushing in the compression zone at mid-span, as illustrated in Figure 6(a). From Figure 5(a), it is evident that the peak strength of the specimens without stitch (i.e. the control specimen) and those with stitch are approximately the same. The difference in the peak strength between the specimen with a 50 mm stitch and that with a 100 mm stitch is marginal.

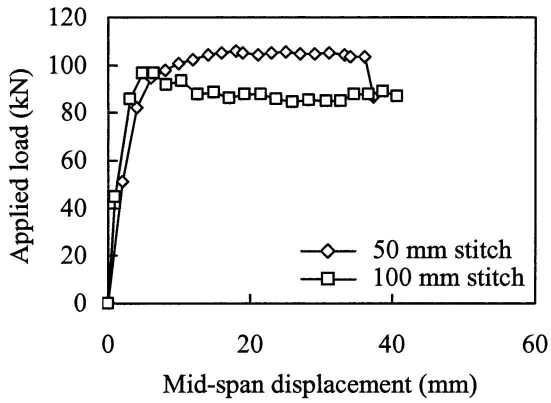
When the stitch is subject to pure shear, the behaviour of the specimen is brittle. As the peak strength is reached, a large diagonal crack suddenly forms across the stitch (Figure 6(b)) and the strength drops abruptly. It can be seen from Figure 5(b) that regardless of the size of the stitch, the peak strengths of the specimens are nearly the same.



(a) Case (i)



(b) Case (ii)

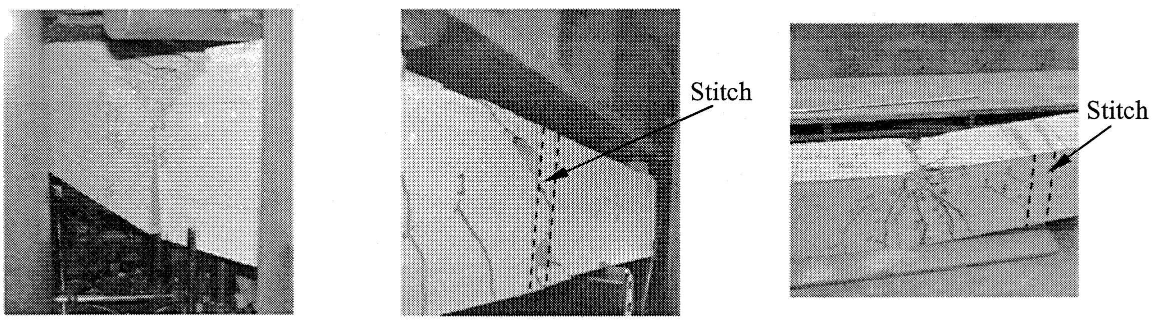


(c) Case (iii)

Figure 5 Load-displacement relationships for beam specimens with stitch subjected to different internal forces

From Figure 5(c), it is evident that the behaviour of the specimens of Case (c) is ductile. Failure of the specimens is localized at the point of loading where there is significant cracking and crushing of concrete; while at the stitch, slight opening of the construction joint is observed and several diagonal cracks are found propagating from the construction joint towards the point of loading. The condition of the beam at failure is illustrated in Figure 6(c). For the specimen with a 50 mm stitch, the peak strength is approximately 100 kN, while that for the specimen with a 100 mm stitch is approximately 110 kN. The peak strengths of the two specimens are relatively close to each other.

The results suggest that the width of the stitch has minimal effect on the strength of the stitch within the maximum width of stitch studied. The ductility of the specimens is also not affected by the width of the stitch but rather by how the specimen is loaded.



(a) Case (i) (b) Case (ii) (c) Case (iii)

Figure 6 Failure modes of beam specimens

Shear Specimens

The load-displacement relationships of the five shear specimens tested are plotted in Figure 7. The shear displacement is the relative vertical displacement between the two precast units. All shear specimens are identified as explained below. Using E-K(M)-100-60-2 as an example, the first field represents the type of prestressing used, with 'E' indicating external prestressing; the second field represents whether the stitch is plain or with shear keys, with 'K(M)' indicating stitch with two shear keys, 'K(S)' indicating stitch with single shear keys, and 'P' indicating plain stitch with no shear key; the third field indicates the width of the stitch in mm; the fourth field indicates the grade of concrete in MPa; and the fifth field indicates the prestress applied to the stitch in MPa. Therefore, a specimen identified as E-K(M)-100-60-2 is composed of Grade 60 concrete with external prestress of 2 MPa applied and two shear keys are provided to the stitch that has a width of 100 mm.

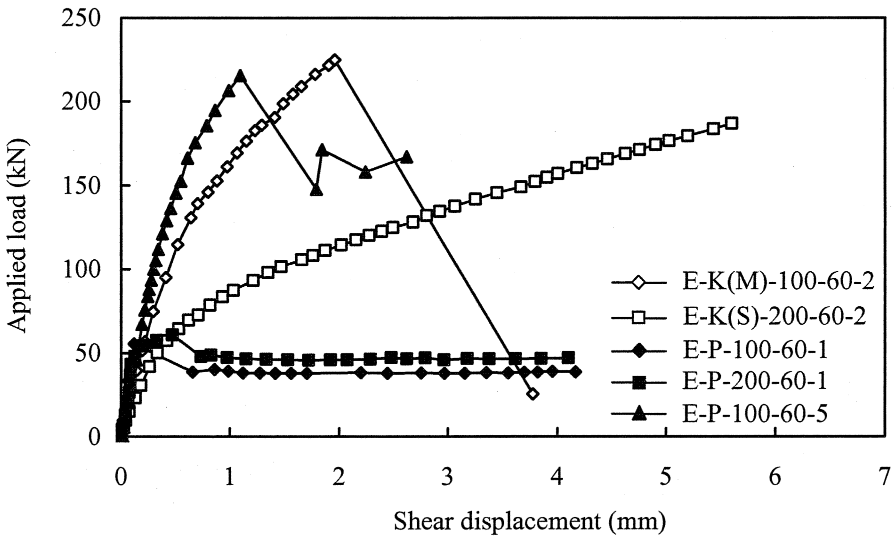


Figure 7 Load-displacement relationships for the shear specimens

The specimens with plain stitch are first discussed. From Figure 7, it can be seen that the behaviour is largely the same for both specimens E-P-100-60-1 and E-P-200-60-1. The peak strengths of the two specimens are between 50 to 60 kN, which once again demonstrates that the width of a plain stitch has little effect on its strength. It is evident that as the prestressing level is increased to 5 MPa (E-P-100-60-5), the peak load-carrying capacity is significantly increased to approximately 220 kN. Therefore, the level of prestressing has marked influence on the load-carrying capacity of the stitch. For specimens with plain stitch, the failure mode is characterized by sudden occurrence of sliding along one or more of the construction joints. Upon failure, the strength of the stitch is mainly contributed by friction from sliding between the surfaces of precast unit and in-situ stitch. As observed from the load-displacement curves, a long smooth plateau is evident in the post peak range for specimens E-P-100-60-1 and E-P-200-60-1, which can be modelled as Coulomb friction. For specimen E-P-100-60-5, the post-peak behaviour as shown in Figure 7 is not as smoothed. Since the prestressing force is substantially higher, the resistance against sliding by the aggregates along the construction joint becomes very large. As the applied load is large enough to overcome that resistance, sudden slippage along the construction joint occurs and the load drops. Subsequently the resistance builds up again and sudden slippage occurs again when the resistance is overcome by the applied load. Therefore the post-peak branch of specimen E-P-100-60-5 has a "zig-zag" shape. This observation also implies that the roughness of the construction joint should have strong effect on the post-peak strength of plain stitches, which will be examined in due course. Since the post-peak strength of the stitch is mainly contributed by frictional forces, ductility can only be maintained if sufficient prestressing force is provided. Therefore the presence of adequate prestressing force beyond the peak strength of the stitch is crucial in preventing sudden loss of strength in the stitch.

Up to this stage, only two shear specimens with shear keys have been tested. However, the results from the test have already given indication that the behaviour of the stitches with shear keys is quite different from the behaviour of those without shear keys. Upon reaching the peak strength, the stitch of specimen E-K(M)-100-60-1 fails suddenly in a brittle manner by cracking diagonally across the stitch as illustrated in Figure 8 and an abrupt drop in load can be seen in Figure 7. This behaviour is much different from that of the specimens with plain stitches in which the post-peak behaviour is characterized by a long plateau in the load-displacement relationship. This type of stitch has little reserve strength upon reaching the peak load-carrying capacity.

No brittle failure is observed for the specimen with one large key and a wider stitch, i.e. specimen E-K(S)-200-60-1. In fact, the specimen was not loaded to failure during the experiment but was stopped at a load of approximately 190 kN because at that load, the prestressing force was increased to a level that had almost reached the capacity of the load cell used to measure the prestressing force. However, at a load of 190 kN, continuous crack had already formed along the construction joint and there was sliding between the precast unit and the stitch along the joint but the stitch still remained intact.

From Figure 7, it can be seen that the peak load-carrying capacity of specimens E-K(M)-100-60-2 and E-P-100-60-5 are approximately the same. This observation seems to imply same level of load-carrying capacity can be achieved yet less amount of prestressing can be applied by adding shear keys to the stitch.

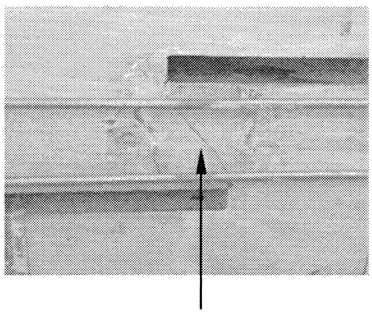


Figure 8 Diagonal cracking across the stitch for specimen E-K(M)-100-60-1

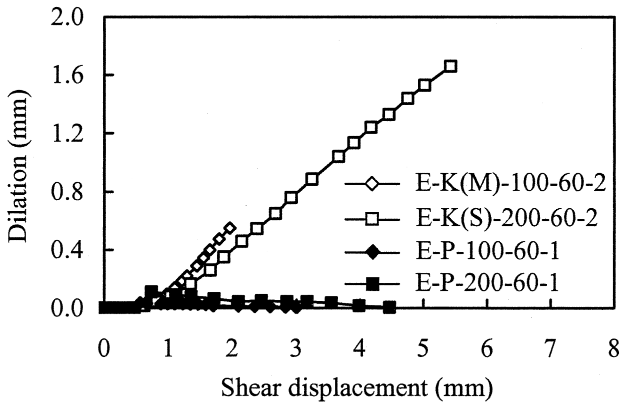


Figure 9 Relationship between shear displacement and dilation (mm)

As aforementioned, there is an increase in prestressing force as load is applied to the specimens with shear keys. This behaviour is caused by dilation in the stitch as the shearing load is applied. Dilation is taken as the displacement between the precast units measured along the horizontal centreline of the stitch. The effect of dilation is much more pronounced for specimens with keyed stitches than those with plain stitches. The relationships between shear displacement and dilation of the various specimens are plotted in Figure 9. For the specimens with plain stitch, dilation is relatively insignificant compared to the dilation in the specimens with keyed stitch. The stress in the tendon can be increased due to dilation. The effect of dilation on tendon stress is rather insignificant for a segmental bridge with unbonded tendon because the strain increase due to dilation will be averaged along the entire length of tendon between end anchorages. However, for segmental bridges prestressed by bonded tendon, dilation may cause substantial increase in strain at the location of the stitch, which can potentially overstress the tendon. Specimens with stitch prestressed by bonded tendon will be tested in the near future and the effect of dilation on tendon stress will be investigated in due course.

CONCLUSIONS

Extensive experimental studies have been carried out to investigate the behaviour of in-situ concrete stitches subject to a combination of internal forces and subject to direct shear by conducting a series of loading tests on the beam specimens and shear specimens respectively. Detailed coverage on the setup of the specimens and load testing has been included in this paper. Based on the results of the tests conducted so far, several preliminary conclusions can be drawn:

(a) The width of plain in-situ concrete stitch does not appear to have significant effect on the peak-load carrying capacity of the stitch regardless of the combination of internal forces that it is subjected to.
(b) The strength of the in-situ concrete stitch is strongly influenced by the level of prestressing applied and the strength of the stitch increases as the level of prestressing increases.
(c) For plain in-situ concrete stitches, failure occurs along the construction joint. Strength in the stitch is still present beyond the peak strength and it is mainly contributed by the frictional force from the sliding between the surfaces of precast unit and stitch.
(d) By providing shear keys to the concrete stitch, the level of prestressing can be reduced to achieve the same strength as those stitches without key. However, this may result in a brittle failure.
(e) For keyed concrete stitches, the amount of dilation is significantly higher than that of plain stitches. For segmental bridges prestressed by bonded tendon, this may have marked effect on the stresses of the tendons.

With further testing on the specimens being carried out in the near future, it is expected that more definitive conclusions can be drawn on the behaviour of the in-situ concrete stitches.

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