NUMERICAL ANALYSIS OF IN-SITU STITCHES IN PRESTRESSED CONCRETE SEGMENTAL BRIDGES

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ABSTRACT

Prestressed concrete segmental bridges are widely used as they can easily adapt to various site conditions. The in-situ concrete stitches in the construction of these bridges are subject to complicated stress conditions and they are therefore potential weak points in the structure. However relatively little work has been done in this regard. This paper describes the finite element analysis of mechanical behaviour of in-situ stitches by using the package Midas FEA and the results which include the ultimate capacity and post-peak responses under shear. In developing the nonlinear finite element models, various interface elements are employed to simulate the construction joint between precast and cast in-situ concrete components. Shear models with and without keyed joints are studied, the results of which are compared with experimental data to ensure reasonable agreement. After the determination of input parameters and the verification with experimental results, the numerical model is used to supplement the experimental programme and predict the behaviour of such in-situ stitches in general. In addition, an in-depth study is conducted to investigate the influence of different prestressing forces. Moreover, an elementary model of full-scale in-situ stitch is presented in order to estimate the complete structural behaviour. The outcome of this paper will be used to evaluate not only the strength and ductility of isolated elements, but also the robustness and serviceability of full-scale bridges.

KEYWORDS

In-situ stitches, interface elements, prestressed concrete, segmental bridges, shear.

INTRODUCTION

Precast segmental construction has been widely used in bridge structures over the recent decades, owing to its efficiency in building the superstructure and versatility in adapting to site conditions. By introducing the balanced cantilever method, the need to erect costly falsework can be minimized as compared to other types of bridges. With the aid of prestressed concrete technology, segmental bridge construction brings economic advantages in the range of long spans. However, in order to fill the gap between two adjacent cantilevers built up of precast segments, it is still necessary to make the final connection by a cast in-situ concrete stitch around 200mm in width. Usually the in-situ concrete stitches are not provided with longitudinal reinforcement, which makes them the potential weak links in precast segmental bridges. Although longitudinal prestressing tendons are employed to resist the sagging moment around the mid-span location, the hogging moment and shear capacities of the stitches are not as reliable. Due to the continuity of bridge deck, any unexpected failure of one stitch will lead to moment redistribution among adjacent spans, possibly causing hogging moments in other stitches, and hence a progressive collapse may be triggered.

Extensive research work has been conducted on the behaviour of dry joints and epoxy joints (Buyukozturk *et al.* 1990; Zhou *et al.* 2005; Turmo *et al.* 2006), the performance of prestressed concrete girders by numerical methods (Ramos and Aparicio 1996) and experimental methods (Takebayashi *et al.* 1994; Oh and Chae 2001; Megally *et al.* 2003a&b), whereas little work has been done on in-situ concrete stitches. The philosophy of robust design requires that every structural component should possess sufficient spare capacity to cope with extreme scenarios such as earthquakes or terrorist attack. In light of this, the in-situ concrete stitch requires special attention and proper detailing, as it plays an essential role in ensuring adequate redundancy in the structure. In this study, two-dimensional finite element models are developed for analyzing the performance of in-situ stitches under shear loading. Two types of specimens, namely the stitches with plain and keyed joints, are examined. The study on variation of prestressing provides an insight into the pre-peak and post-peak behaviour of stitches. The results are used to provide some guidance on detailing the design of stitches.

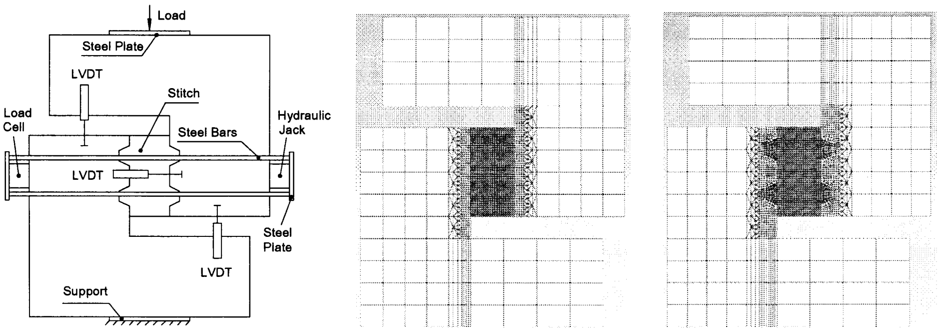
NUMERICAL STUDY

Experimental tests of stitches under shear are carried out using the setup as shown in Figure 1(a). In the laboratory tests, the main variables are the stitch width (100mm and 200mm), prestressing level (1MPa and 5MPa), and joint type (plain and keyed). Each specimen is labelled as in the following example: E-P-100-60-1, where "E" stands for external prestressing, "P" stands for plain joint, "100" stands for stitch of 100mm gap width, "60" stands for the concrete grade, and "1" stands for prestressing level in MPa. An inherent shortcoming of experimental investigation is the difficulty in exploring various parameters. Therefore, in an effort to analyze the behaviour of stitches under various conditions, a comprehensive study using the finite element method is conducted using the package Midas FEA (Midas Information Technology, 2009), and the experimental results are used to verify the input parameters and outcomes of the finite element models. Two-dimensional (2-D) finite element models are developed using triangular and quadrilateral plane stress elements to simulate the behaviour of experimental specimens, as shown in Figures 1(b) and 1(c). Quadrilateral elements are used mostly in the mesh, except for the areas of shear keys where triangular elements have been used in order to get better results (MacLeod, 2005). The material properties for the specimens, such as Young's modulus and tensile strength of concrete, are determined in accordance with the formulae given by Lee *et al.* (2000) and Kwan *et al.* (2001).

Interface elements are used to simulate the construction joint between precast and cast concrete components. A friction model for sliding between concrete surfaces can be developed according to Coulomb's law (Kafali *et al.*, 2007), i.e.

$$\tau = \sigma \tan \varphi + c \qquad (1)$$

where τ is the shear stress, σ is the normal stress, φ is the internal frictional angle and c is the cohesion. As the softening phenomenon can be observed from the experimental load-displacement curves at the post-peak stage, both the internal frictional angle φ and cohesion c should be reduced accordingly. The internal frictional angle is taken to be 29.65° for static friction and 22.50° for sliding friction as suggested by Mendez *et al.* (2008), and the initial cohesion is determined solely by the peak load. Assuming that the cohesion at the construction joint is contributed by aggregate interlocking and chemical bonding, when sliding takes place, the part from chemical bonding should have vanished. By applying least-squares regression to the experimental data, the increment of cohesion in the softening process is approximately -0.4N/mm^2 within the 1mm range of relative displacement at the interface, where the minus sign indicates reduction. For convenience in computation, linear softening of cohesion is assumed. In practice, it is extremely rare to have failure occurring at both interfaces simultaneously. Therefore, one of the interfaces is deliberately given a slightly higher cohesion, so that only the weaker interface will fail. The dilatancy angle, another significant parameter in the Coulomb friction theory, reflects the degree of expansion in the direction perpendicular to shear deformation. In the laboratory tests, the load cell measures the changes in prestressing force, which result from tendon extensions caused not only by the stitch dilation, but also by the relative shear displacements. In this research project, the dilatancy angle is estimated based on the increment of prestressing force measurement. The value of interfacial tensile strength is comparatively uncertain, but it can still be assumed to be smaller than the tensile strength of concrete. The interfacial tensile strength can be determined by calibrating the finite element model with experimental data particularly at the pre-peak stage. The input parameters of the finite element model are listed in Table 1.



(a) Experimental setup (b) Mesh of plain joint (c) Mesh of keyed joint

Figure 1. Loading test of shear specimens

Table 1. Input parameters of modelling

Concrete		Steel		Interface	
Elastic Modulus:	25.3GPa	Elastic Modulus:	200GPa	Type of Nonlinearity:	Coulomb Friction
Poisson's Ratio:	0.2	Poisson's Ratio:	0.3	Cohesion:	0.7~1MPa
Constitutive Model:	Total Strain Crack	Constitutive Model:	Von Mises	Internal Frictional Angle:	$\varphi = 29.65°$
Tension Function:	Brittle $F_{ct} = 2.7$MPa	Yield Stress:	$f_y = 460$MPa	Dilatancy Angle:	$\psi = 0.5° \sim 1°$
Compression Function:	Thorenfeldt $F_c = 51$MPa			Tensile Strength:	$F_{ct} = 2$MPa
Shear Function:	Constant $\beta = 0$				

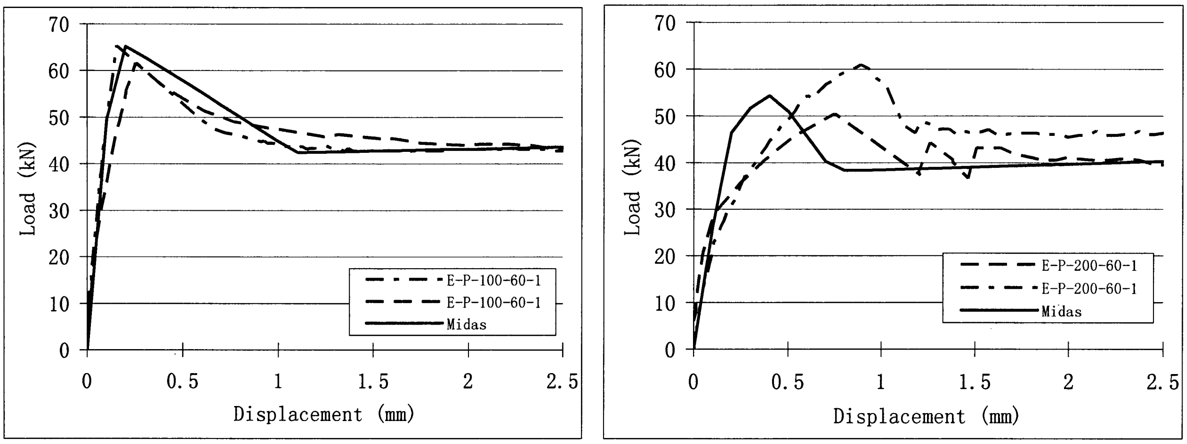
RESULTS OF FINITE ELEMENT ANALYSIS

Figures 2 and 3 compare the finite element results with the corresponding experimental data, which show that the chosen material parameters are appropriate. It can be seen that the plain joints exhibit more ductile post-peak behaviour than the keyed joints. However the keyed joints reach higher peak loads approximately four times those of the plain joints. The peak and residual strengths of then 100mm and 200mm plain stitches are similar, although the 200mm plain stitch shows apparent nonlinearity before reaching the peak owing to significant flexural cracking of the specimens and around the interfaces. The failure mechanisms obtained from the finite element models are depicted in Figure 4, which show obvious interfacial sliding of the plain joints. Because of the resistance provided by shear keys, only limit sliding occurs at the keyed joints, but the rotation of stitch is significant. Along with the rotation, the horizontal elongation of the external tendon results in significant increment of prestressing force because of the relatively short tendon length between anchorages, which makes it too dangerous to increase the experimental loading on specimen E-K(S)-200-60-2 any further. The finite element model estimates the peak load of the 200mm keyed stitch to be 284kN with 9.2mm displacement. In comparison with the 100mm keyed stitch, the deformation of the 200mm keyed stitch is much greater, with a relatively small increase in peak load.

Figure 4(a) implies that the peak and residual strengths of the plain stitches are mainly contributed by the friction at interfaces. However Figure 4(b) indicates that the keyed stitches fail by splitting of concrete along the diagonal direction of the stitch, resulting in brittle failure. From the calculated major principal strain plots of keyed stitches before failure shown in Figure 5, it can be seen that a strut effectively forms within the stitch. Experimental observations have confirmed this postulation, as a major crack invariably develops abruptly along the diagonal direction of stitch, which is parallel to the strut predicted by the finite element model. Actually the failure of the 200mm keyed stitch is predicted by finite element model to be due to the yielding of tendon rather than the splitting of concrete. However it should be pointed out that this is largely affected by the experimental setup with relatively short tendon length between anchorages.

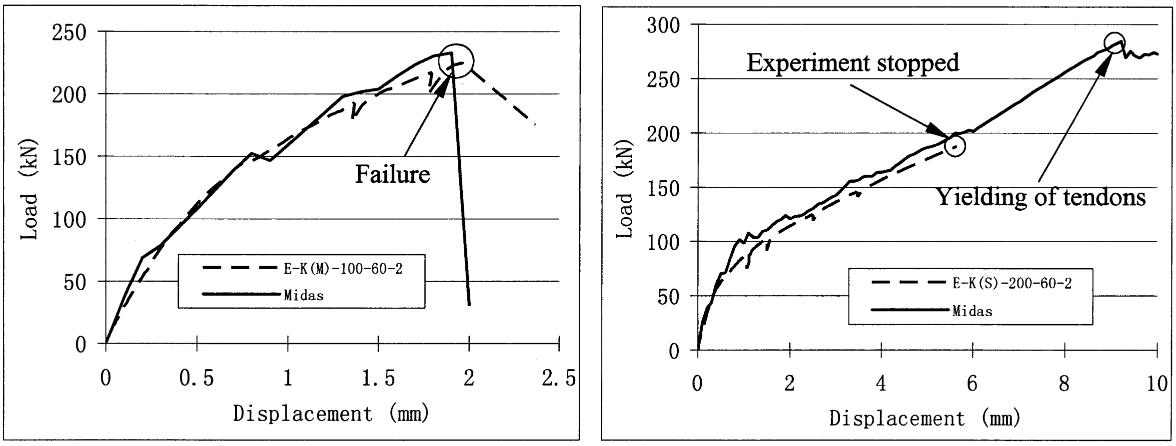
The effects of initial prestressing are then investigated. The load-displacement curves computed by the finite element models of the plain and keyed stitches for various initial prestressing are shown in Figures 6 and 7 respectively. As predicted by Coulomb's law, higher normal stresses imposed on the plain joint interfaces result in higher peak capacity and residual shear strength. However Figure 6 shows that the softening phenomenon is more distinct in the 200mm stitches than in the 100mm stitches. As a wider stitch under prestressing involves more elastic energy absorption, once the crack at the joint interface propagates, the release of elastic energy and the process of softening are more rapid within the same relative displacement between the two precast components.

Keyed stitches, on the other hand, behave quite differently from plain stitches as initial prestressing increases. Figure 7(a) indicates that, while higher initial prestressing tends to stiffen the stitch more, the peak shear strengths of 100mm keyed stitches are not much affected. Therefore the deformability, or the capability of the stitch in sustaining deformation, tends to decrease with increase in initial prestressing. The performance of 200mm keyed stitches as shown in Figure 7(b) is to certain extent similar. Compared to the 100mm stitches, the 200mm stitches are more flexible because of the increased thickness of in-situ concrete. Higher initial prestressing also tends to stiffen the stitch more. Because of the higher dilation associated with the higher deformations, the tendon forces have increased so rapidly that the specimens fail by yielding of tendons first. This rapid increase in tendon forces is partly due to the dilation caused by the bodily rotation of the stitch concrete as shown in Figure 4(b). As mentioned before, this is largely affected by the experimental setup with relatively short tendon length between anchorages. Further refinement of the setup is necessary in order to simulation the actual site conditions.



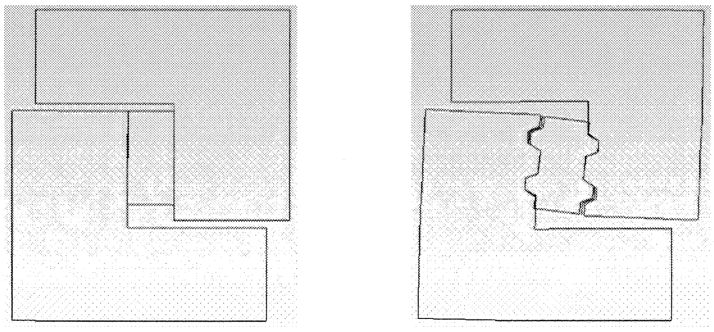
(a) 100mm stitch (b) 200mm stitch

Figure 2. Performance of plain stitches



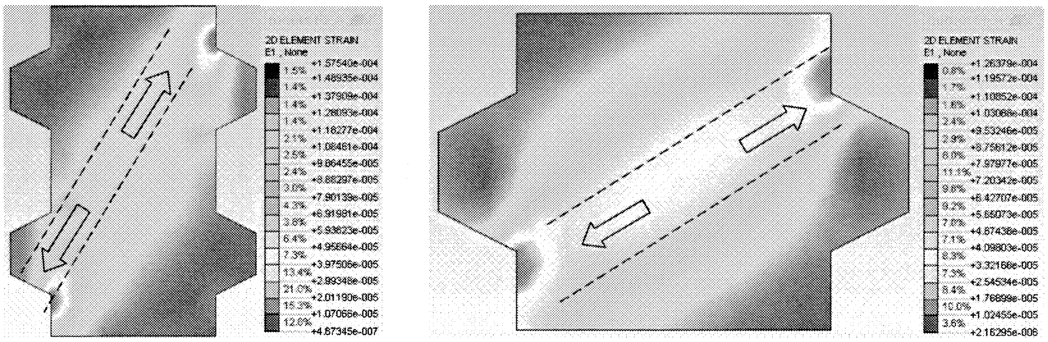
(a) 100mm stitch (b) 200mm stitch

Figure 3. Keyed stitch (finite element model verification)



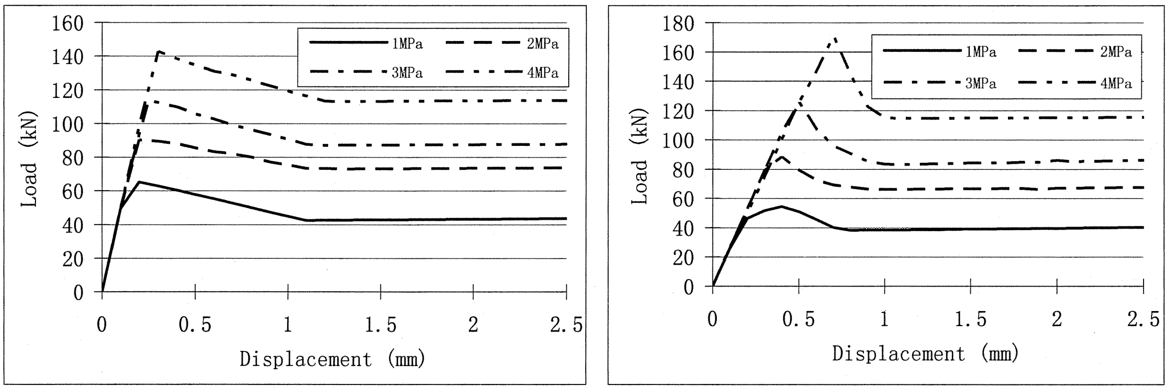
(a) Plain stitch (sliding) (b) Keyed stitch (concrete splitting)

Figure 4. Failure mechanisms of different stitches



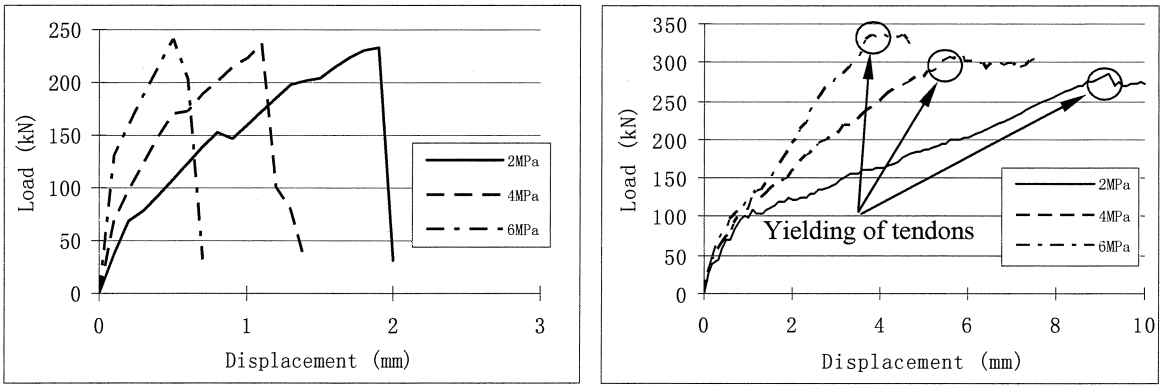
(a) 100mm keyed stitch (b) 200mm keyed stitch

Figure 5. Major principal strain plots of keyed stitches showing the hypothetical struts



(a) 100mm (b) 200mm

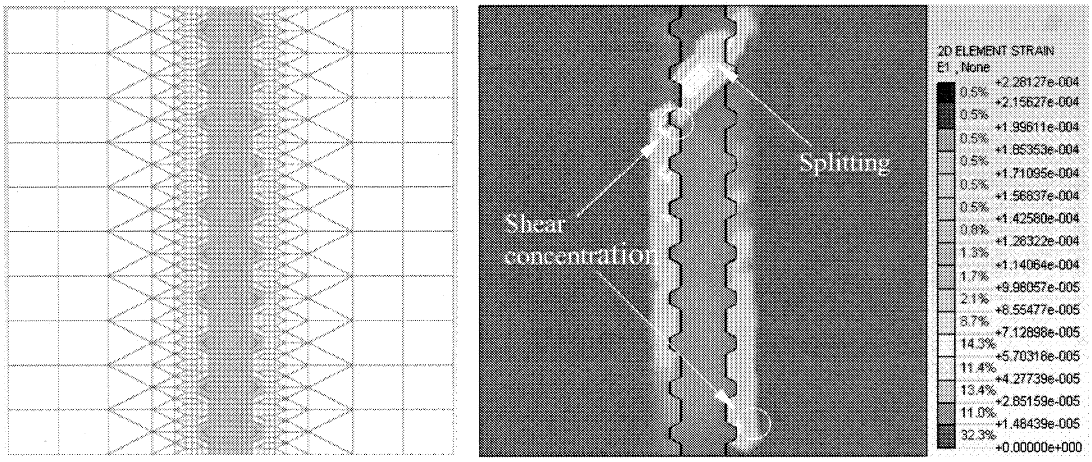
Figure 6. Effects of initial prestressing on behaviour of plain stitches



(a) 100mm (b) 200mm

Figure 7. Effects of initial prestressing on behaviour of keyed stitches

A finite element model of full-scale in-situ stitch with shear keys is built up as shown in Figure 8(a) Analysis is carried out by imposing relative vertical displacement on both sides after applying the prestressing in the longitudinal direction and a typical level of sagging moment. The failure of this multi-keyed stitch is also due to the splitting of concrete, but only one internal strut has formed diagonally between two adjacent keys as shown in Figure 8(b) rather than along a steeper diagonal direction associated with the total depth of stitch,. Therefore it is reasonable to assume that the shear strength of the full-scale stitch is still governed by the tensile strength of concrete and is largely associated with the shear capacity of a single-keyed stitch. However, the shear lag effect induces shear concentration on end keys. Intuitively, the degree of non-uniform distribution of shear stresses and deformations around the keys along the depth tends to increase with the ratio of depth to width of stitch. Hence the behaviour of multi-keyed stitch cannot be simply assumed to increase with the depth of girder or the number of shear keys. Further investigation in this aspect is necessary.



(a) Model and meshing (b) Major principal strain plot at failure

Figure 8. Behaviour of full-scale in-situ stitch

CONCLUSIONS

This paper has described the analysis of the mechanical behaviour of plain and keyed stitches under shear by using finite element method, with special emphasis on the failure mechanisms of various types of stitches. The shear resistance provided by the plain joint interface is limited although it can be enhanced by applying higher initial prestressing. The keyed joints are proved to be very effective in transferring the shear load compared with the plain joints. The shear capacity of a keyed stitch is governed by the tensile strength of concrete. Although initial prestressing tends to stiffen the stitches, it has little effect on the shear resistance while it also reduces the deformability. Measures to enhance the deformability of keyed stitches and to avoid brittle failure there are therefore advisable. The results obtained from specimens of stitches should be interpreted properly when they are applied to the design of full-scale in-situ stitches. Further studies are recommended.

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