Flexural Behaviours of Box Segmental Beams with Internal Tendons Subjected to Repeated and Static Loads

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Abstract. The main objective of this study is to gain a better understanding of the behaviours of different types of joints when box segmental beams are subjected to bending. Five beams with internal tendons were thus produced and tested: one beam was cast monolithically as a reference beam and four were formed as segmental beams. All beams were produced using Self Compacting-Concrete (SCC) in box sections. Each segmental beam was formed by assembling three precast concrete segments with four post-tensioning tendons. The segmental beams had the same general characteristics, but with different types of joints between the segments. Four types of joints were adopted in this study:- dried, epoxied, dried strengthened with carbon fibres and multi-steel shear keyed joints. All beams were tested under two types of loadings, repeated and static. A test of repeated loading was carried out by exposing each specimen to three loading cycles. Each cycle was implemented by subjecting each specimen to up to 40% of the ultimate load then releasing the loads to return the specimen to the non-loading case. The test of static loading was carried out at the same rate of loading as the repeated load test, and all girder specimens were tested up to failure. The loads versus deflections at specified points were recorded for each 5 kN. Cracking, mode of failure and ultimate load values were recorded, along with the concrete surface strains at specified locations for both loadings. The tests results for repeated loading showed that joint type had a clear effect on behaviours in the segmental beams, which had deflection readings ranging from 16 to 61% higher than that of the monolithic (reference) beam, as well as higher tensile strain than seen in the reference beam, by 8 and 67%. Similar effects of joint type were observed under static test. At the first crack loading, the segmental beams had deflections of between 8 and 94% and tensile strains of about 5 to 18% more than the reference beam. The failure modes of the tested beams were all different. Failure of the dry joint occurred in the segment interface, while the failure of each epoxied joint and joint strengthened by carbon fibres developed in the concrete adjacent to the segment interface. The steel shear keys clearly transfer the shear resistance to the concrete parts adjacent of the joints.

1. Introduction

The precast segmental construction method of building concrete bridges has many advantages. This construction method helps ensure concrete quality during pouring, reduces workload on the construction site, speeds up construction, and mitigates disturbance to the environment. Moreover, the dimensions of the cross section, especially the dimensions of webs and flange, can be reduced due to internal tendons being placed inside the concrete; thus, the deadweight of internal prestressed bridges...
can be reduced. As compared with ordinary monolithic bridges, many other advantages are offered by segmental construction methods such as small light segments, structures with no cracks due to opening of dry joints, recycling of damaged segments, no interruption of traffic, and shorter construction time. However, bridges of this kind do have some disadvantages compared with monolithic bridges, as longitudinal steel bars are interrupted at the joints in segmental bridges, and deck segments are connected directly (dry joints) or indirectly (strengthen joints) by prestressing. These joints between deck segments thus represent locations of discontinuity in such bridges. and previous studies have not totally uncovered the effect of such discontinuities on the behaviours of joints in segmental bridges; thus, more research is needed. A description of the construction of a post-tensioned segmental beam and a comparison between experimental structural behaviours with theoretical calculations was presented by Tito et al. (2011) [3]. Several experimental works have also been reported on the SPPRC beams [5,4,8]. In these works, behaviors of segmental concrete box beams with internal and external tendons under bending were evaluated Experimental studies were carried out on precast concrete segmental beams with internal and external tendons [6,7,11], for evaluation of the flexural behaviours of SPPRC beams with external tendons a compared with internal tendons under combined shear and bending. The response of reinforced concrete precast spliced girders to static and impact loads was studied by Al-Bayati Mays [9], and an experimental study to analyse the mechanisms of combined shear and bending resistance for dry and epoxied joints with loads are located in the immediate vicinity of the joint along with the simplified failure modes of dry and epoxied joints subjected to combined shear and bending were presented by Yang and Yi (2016) [10]. The difference in strength between on-site cast and precast segmental concrete was assessed to accurately evaluate the deflection of precast concrete flexural members with joints within lapped splices by Park et al. 2017 [14], while a study to investigate the use of CFRP tendons as replacements for traditional prestressing steel tendons for PSBs to deal with corrosion-related issues was reported by Pham, Le and Hao (2018)[12]. Al-Sherrawi , Allawi, AL-Bayati, Al Gharawi and El-Zohairy showed that the structural behaviours of Segmental Precast Post-tensioned Reinforced Concrete (SPPRC) beams largely depends on the behavior of the joints that connect the segments [13]. In the current research, a series of static tests were carried out to investigate the behaviours of full-scale SPPRC beams with different types of epoxy-glued joint configurations: multi-key joint, single key, and plain key joint. The shear capacity predicted by the AASHTO [1] equation diverges from that predicted by numerical analysis at high confining pressure, because of the contribution of friction in the total shear capacity decreasing with an increase in confining pressure [2].

2. Experimental Program

2.1 Details of specimens

This study investigated five beams: one of them was produced monolithically as a reference and the others were segmental beams. Each segmental beam was fabricated with three precast concrete segments of 700 mm length using a post tensioning technique. The total length of each specimen was this 2100mm and box sections with total dimensions of 300mm×300mm and hollows of 140mm×140mm were adopted for all beams. All segments were reinforced with four steel bars of Φ 10 mm for bending and with Φ 8 mm @ 120 mm c/c for stirrups as seen in , Figure1.
2.2 Joints Design
To achieve the goal of this research, four types of joint were adopted to evaluate the flexural behaviours of segmental beams under bending stresses, as illustrated in Table 1.

| Symbol of Beam | Description of Joint                                      |
|----------------|------------------------------------------------------------|
| SB1            | Dried joint                                                |
| SB2            | Epoxied joint                                              |
| SB3            | Dried joint strengthened by carbon fibres with epoxy resin |
| SB4            | Multiple steel keyed joint                                 |

2.3 Materials
Ordinary Portland cement of 53 grade corresponding to ASTM type I was used throughout the investigation. Locally available crushed granite gravel with a size of 5 to 12 mm was used as coarse aggregate. Locally available clean river sand was used as a fine aggregate per the specifications. ViscoCrete 5930-L superplasticizer was added to mixing materials in order to improve workability. silica fume and limestone powder in specified quantities were added to improve mechanical properties of the concrete. A Self-Compacting Concrete (SCC) type was used to produce all beams of this study using materials above, with mixing proportions as shown in Table 2.

| Cement kg/m³ | Fine Agg. kg/m³ | Coarse Agg. kg/m³ | Silica Fume % of wt. of Cement | Powder kg/m³ | ViscoCrete % | w/c % |
|---------------|-----------------|-------------------|--------------------------------|--------------|--------------|-------|
| 470           | 750             | 900               | 23                             | 130          | 2.45         | 0.39  |

2.4 Post-Tensioning Procedure
After the precast concrete segments were cured for 28 days outdoors, they were subjected to prestressing forces to form segmental specimens by means of four tendons in each specimen. PVC ducts of 18 mm diameter were embedded in concrete bodies to accommodate the post- tensioning
strands after concrete hardening. The pre-stressing strands were seven-wire, of 12.7 mm in diameter, and cross-sectional area of 92.6 mm$^2$, 0.1% proof yield and ultimate strengths of 1570 MPa and 1860 MPa respectively. The post-tensioning operation was done in three stages to stretch each tendon to 250 bar, equivalent to 100.5 kN. Pre-stressing anchor heads and wedges were fixed to all tendons’ stressing ends. A (10mm) steel plate of dimensions 10×10cm was used at each end of tendon as a bearing plates.

2.5 Testing Setup
2.5.1 Testing Setup
The tests were performed in the Structures Laboratory in the civil Engineering department of Mustansiriyah University. All the beams were tested using two loading configurations on the test setup shown in Figure 2. The loads applied over the beams were provided by two jacks, which were located on a reaction frame anchored to a strong floor. Two steel rods with diameter 50 mm were used to transfer the vertical loads as two point loads to the specimen.

2.5.2 Instrumentation
Measurements recorded during each test included applied loads, beam deflections, and strains.
1. Two strain gauges were placed on the lower and upper sides of mid span position of the beams to measure the maximum concrete strains under tension and compression.
2. A dial gauge with 0.01mm accuracy and 30mm range was installed at mid span underneath the bottom face of each test beam to measure the vertical deflection.

2.6 Testing procedure
2.6.1 Repeated loading test
This test was carried out by exposing each beam to three loading cycles. Each cycle was implemented by loading each beam up to 70 kN and releasing the load returning the beam to the non-loading case. The 70 kN value was previously determined by testing an experiential beam under static load up to failure at ultimate load of 177 kN; 40% of that ultimate load was taken to be a maximum limit of repeated loads to evaluate stiffness in the tested beams within the elastic stage, Figure(3). The deflection and strain versus each 5 kN load were measured at mid span position.
2.6.2 Static loading test
The loading was applied slowly at small increments of about 5 kN. The deflections and strains were recorded. Once cracking of concrete was observed (first crack), the load was recorded. The tests were continued up to failure, where the ultimate load was recorded.

3. Results and Discussions
3.1 Results of Repeated Load Tests
3.1.1 Deflection results
The test results for deflection versus peak load 70 kN, which represent the maximum deflection of each repeated load are shown in Table 3 for all tested beams, and the load-deflection relationships are illustrated in Figures 3, 4, 5, 6, and 7.

| Beams | No. of loading cycle | $\Delta_{70}^a$ (mm) | $(\Delta_{70})_b^b$ (mm) | $\Delta_{70}/(\Delta_{70})_c^c$ |
|-------|----------------------|----------------------|-----------------------|----------------------|
| RB1   | 1                    | 0.70                 | 0.88                  | 1.00                 |
|       | 2                    | 0.79                 |                       |                      |
|       | 3                    | 1.14                 |                       |                      |
| SB1   | 1                    | 1.22                 | 1.42                  | 1.61                 |
|       | 2                    | 1.41                 |                       |                      |
|       | 3                    | 1.62                 |                       |                      |
| SB2   | 1                    | 0.99                 | 1.11                  | 1.26                 |
|       | 2                    | 1.08                 |                       |                      |
|       | 3                    | 1.26                 |                       |                      |
| SB3   | 1                    | 1.10                 | 1.31                  | 1.49                 |
|       | 2                    | 1.28                 |                       |                      |
|       | 3                    | 1.55                 |                       |                      |
| SB4   | 1                    | 0.96                 | 1.02                  | 1.16                 |
|       | 2                    | 1.01                 |                       |                      |
|       | 3                    | 1.06                 |                       |                      |

Table 3. The test results of maximum deflections of each repeated load

a Deflection versus 70 kN load.
b Average deflection of three repeated loadings.
c Average deflection of three repeated loadings for control (reference) beam.

This shows all beams have slightly differences in deflection, with the average deflection values of the three repeated loading tests being about 0.88 to 1.42 mm and behave in same manner at this stage of loading.

From Table 3, the epoxied and keyed joint types for beams SB2 and SB4 maintain strength and stiffness at a level approaching that of reference beam RB1 due to the stiffness of the concrete adjacent to the epoxied joint surface for beam SB2 and the high shear stress capacity of the steel keys for specimen SB4 in addition to the vertical component add by the post tensioning tendon in both types of joints.

As the dry joint cannot resist tensile stress, the beam with dry joint type SB1 showed the highest deflection compared with other segmental beams.

**Figure 4.** Load-Deflection relationship for RB1

**Figure 5.** Load-Deflection Relationship for SB2

**Figure 6.** Load-Deflection Relationship for SB4
However, using high resistance tensile stress carbon fibres with epoxy resin, to enhance the correlation between segments joints for beam (SB3), showed a good effect in term of increasing the stiffness and reducing the deflection of this beam in comparison with reference beam RB1 as seen in Figure (7).

![Figure 7: Load-Deflection Relationship for beam SB3](image)

### 3.1.2 Strain results

The test results for strain are given in Table 4, which lists the maximum tension and compression strains for three repeated loadings in addition to the average value.

| Beams | $(\varepsilon_t)_{a} \times 10^{-6}$ | $(\varepsilon_c)_{a}/(\varepsilon_c)_{b}$ | $(\varepsilon_t)_{a} \times 10^{-6}$ | $(\varepsilon_c)_{a}/(\varepsilon_c)_{d}$ |
|-------|------------------------------------|---------------------------------|------------------------------------|---------------------------------|
| RB1   | 141                               | 1.00                            | -153                               | 1.00                            |
| SB1   | 235                               | 1.67                            | -314                               | 2.05                            |
| SB2   | 160                               | 1.13                            | -230                               | 1.50                            |
| SB3   | 172                               | 1.22                            | -241                               | 1.58                            |
| SB4   | 152                               | 1.08                            | -162                               | 1.06                            |

a,c Average of tensile and compressive strains for three repeated loadings.
b,d Average of tensile and compressive strains for three repeated loadings of control beam

Segmental beam SB1, which was produced with a dry joint type, recorded maximum strains in tension and compression greater than those of the monolithic beam RB1 by about 67% and 105%, respectively.

This behaviour of beam SB1 can be attributed to low resistance of the dry joint between the segments under tensile bending stress due to the discontinuity of concrete and cut off longitudinal reinforcement at the joint position.
To clarify this, the relationships between loads and the average values of the three repeated loadings for segmental beam SB1 and the reference beam RB1 are illustrated in Figures 8 and 9.

**Figure 8.** Strain results of three repeated loadings for beam SB1.

**Figure 9.** Average strains of three repeated loadings for RB1 and SB1.

The test results for beam SB2 were included in Table 4 and clarified in Figures 10 and 11. From Figure 10, the difference interval in the strain results among the three cycles loading at tension was lower than that seen in compression; this can be attributed to the improvement in tensile behaviour of beam SB2 from the epoxied joint type.

From Table 4, segmental beam SB2 has the maximum strains in tension and compression, greater than those of the monolithic beam RB1 by about 13% and 50%, respectively. From the results, the difference interval in strains recorded by the dry joint specimen SB1 with respect to monolithic beam RB1 was reduced in testing beam SB2; the difference in both maximum tension and compression strains was reduced by about 54%, which can be attributed to the adhesion of the interior concrete faces of the joint using epoxy resin, which enhanced the axial compressive stress of
the prestressing tendons applied on the entire cross section of beam; thus, the strains recorded by the beam SB2 were lower than those of the dry joint beam SB1, as seen in Figure 11.

![Figure 10](image1.png)

**Figure 10.** Strain results of three repeated loadings for beam SB2

![Figure 11](image2.png)

**Figure 11.** Average strains of three repeated loadings of beams RB1 and SB2

The test results for beam SB3 are shown in Tables 1 and 2 and illustrated in Figures 12 and 13. From Figure 12, the strain behaviour of beam SB3 is approximately the same as that of beam SB2, with the average values of the maximum tension strain of the three repeated loadings were about 152×10⁻⁶ and 172×10⁻⁶, respectively, and maximum tension strains were of -230×10⁻⁶ and -241×10⁻⁶, respectively.
The reason for this convergence in results can be attributed to the mechanism used to strengthen the joint position between the segments in beam SB3 using carbon fibres with epoxy resin, which enhanced the joint resistance against the applied tensile stress as compared with beam SB1, offering maximum strain in tension and compression of about 22% and 58% more than that monolithic beam RB1, as seen in Figure (13).

For beam SB3, the area of entire box section strengthened by carbon fibres and epoxy resin was 180000 mm², while that connected by epoxy resin was 70400 mm². Although the area strengthened in beam SB3 larger than that in beam SB2, it had less effect, which can be attributed to two factors; one is that the interface layer of epoxy between the concrete and carbon fibre in beam SB3 was subjected to shear stress unlike that in beam SB2 which was exposed to bending tensile stress. The other reason was that the concrete zone was strengthened in beam SB2 was exposed to more bending tensile stress than in beam SB3.

From Table 4, the strain results recorded by beam SB4 showed the least difference with those of the monolithic beam RB1, with the average values of the maximum tension strain of the three repeated
loadings for beams RB1 and SB4 being about $141 \times 10^{-6}$ and $152 \times 10^{-6}$, respectively, with maximum tension strains of about $153 \times 10^{-6}$ and $-162 \times 10^{-6}$, respectively. This similarity in results can be attributed to the effects of the mechanism used to strengthen the joint position between segments in beam SB4, as shown in Figure 14.

From the results in Table 4, it is clear that the best results for both tension and compression strains were recorded for beam SB4, which had the least differences in strain results with respect to the monolithic beam RB1, of about 8% and 6% in tension and compression, respectively.

Improved in flexural behaviour on using this type of joint can be attributed to several factors such as the high bending strength of the steel keys, the high shear strength provided by the root of the steel keys, the high bond between the steel keys and the longitudinal reinforcement of the segments provided by interlocking and the high adhesion of epoxy resin to the steel keys.

The improvement of the keyed joint resistance was not limited to the tensile stress, but was also reflected resistance to the compressive stress of the compression zone where the joint recorded the least compression strain compared with the reference beam, Figure 15.

\[\text{Figure 14. Strain results of three repeated loadings for beam SB4}\]

\[\text{Figure 15. Average strains of three repeated loadings for beams RB1 and SB4}\]

3.2 Results of Static Load Tests

3.2.1 Deflection results
The static load test results are listed in Table 5 and the load-deflection relationships are illustrated in Figure 16. From the results, the stiffness capacity of the segmental beams with the different types of joints was between 8 and 94 % lower than that of the monolithic beam. The dry joint cannot resist tensile stress, and thus the segmental beam with the dry joint (SB1) had the least stiffness in comparison with all other types of joints.

Table 5. The Results of all beams

| Beams | Load (kN) | Pcr/(Pcr)c | Δcr (mm) | Δcr/(Δcr)c |
|-------|-----------|------------|----------|-------------|
|       | Pcr       | Pu         |          |             |
| RP1   | 195       | 317        | 1.0      | 1.55        | 1.0         |
| SB1   | 90        | 205        | 0.46     | 3.0         | 1.94        |
| SB2   | 125       | 227        | 0.64     | 2.6         | 1.68        |
| SB3   | 112       | 218        | 0.61     | 2.71        | 1.75        |
| SB4   | 155       | 258        | 0.79     | 1.68        | 1.08        |

a Deflection at first crack loading (Pcr).
b Deflection at first crack loading for control beam (Pcr)c.

Figure 16. Load-deflection Relationship for the tested beams

In addition, it was observed that the failure of beam SB1 occurred by the opening the joint at the tensile side when the applied tensile stress exceeded the compressive stress of the axial compression forces of the post-tensioning tendons, and the opening height of joint increased with the increase of the applied loads and the concrete above the joint opening height broke under the compressive stresses approaching the ultimate load, as seen in Figure 17. In comparison with the failure mode of the dry joint, the failure of the monolithic beam occurred with tensile cracks that began from the bottom when the load increased further, the cracks moved further upward, as shown in Figure 18.
The tests results showed that the epoxied joint had higher strength than the dry joint by about 11%, which can be attributed to the effect of the epoxied joint mechanism.

**Figure 17.** Failure mode for SB1.  
**Figure 18.** Failure mode for reference RB1

Improvement in the bending strength of beam SB2 can be observed from the failure mode, in that it occurred in the concrete adjacent to the epoxy layer rather than the joint plane, as seen in Figure 19, and a similar effect was observed for the dry joint strengthened by carbon fibre in beam SB3, as seen in Figure 20.

**Figure 19.** Failure mode for beam SB2  
**Figure 20.** Failure mode for beam SB3

The failure mode of this type of joint, as shown in figure 20, occurred in the plane of concrete adjacent to the edge of carbon fibre layer. Improvement in resistance for both the epoxy joint and the joint strengthen by carbon fibre was not limited to tensile stress, but was also reflected in the resistance of the compressive stress at the upper side of the joints. The keyed joint in beam SB4 had a positive effect compared with other types of joints, with beam SB4 had showing a bending strength of about 81% of that of the monolithic beam. From the failure mode of the multi-keys joint shown in Figure 21, it can be concluded that the high bond strength between the keys of joint and the longitudinal reinforcement of the two segments offers a significant contribution in term of longitudinal reinforcement of the segments, allowing them to resist the tensile stresses caused by applied loads.
3.2.2 Strain results
The test results for strain versus first crack loadings are listed in Table 6 and the load-strain relationships are illustrated in figures 21 and 22.

![Figure 21. Failure mode for beam SB4](image)

| Beams | Pcr (%) | Pcr/(Pcr)c | $\varepsilon_{ct}$ | $\varepsilon_{ccr}$ | $\varepsilon_{ccr}/(\varepsilon_{ct})_c$ | $\varepsilon_{ct}/(\varepsilon_{ct})_c$ | $\epsilon_{ccr}/\epsilon_{ct}$ |
|-------|---------|------------|-------------------|-------------------|---------------------------------|---------------------------------|-----------------------------|
| RP1   | 195     | 1.0        | 402               | -393              | 1.00                            | 1.00                            | 0.98                        |
| SB1   | 90      | 0.46       | 475               | -511              | 1.18                            | 1.30                            | 1.08                        |
| SB2   | 125     | 0.64       | 438               | -488              | 1.09                            | 1.24                            | 1.11                        |
| SB3   | 112     | 0.61       | 454               | -496              | 1.13                            | 1.26                            | 1.09                        |
| SB4   | 155     | 0.79       | 424               | -478              | 1.05                            | 1.22                            | 1.13                        |

a, c. Tensile and compressive strains at first crack loading.

b, d. Tensile and compressive strains at first crack loading for control (reference) beam.

Segmental beams with different type of joints had tensile and compressive strains about 5 to 18% and 22 to 30% higher than that of the monolithic beam, respectively.

It was also observed that segmental beams’ recorded strains on the compression side were greater than that on the tension sides by about 8 to 13%, while opposite behaviours were recorded in the monolithic beam RB1, with compression strain lower than that on the tension side by about 2%.

From Table 6, the segmental beam with the dry joint, SB1, recorded the largest strain in both tension and compression sides in comparison with the monolithic beam RB1, with tensile and compressive strains about 18% and 30% greater than the latter.

Strengthening the dry joint between segments by using carbon fibres with epoxy resin (SB3) enhanced the joint resistance against applied tensile stress, causing strain in tension and compression zones of about 13% and 26% more than in the monolithic beam RB1.

The best results for both tension and compression strains were recorded in beam SB4, which was produced with multiple keyed joint types; this showed the least difference in strain results with respect to the monolithic beam RB1 of about 5% and 22% in tension and compression, respectively.
4. Summary and Conclusions
The test results offered in this paper provided quantitative data to enhance the fundamental understanding of deflections, failure processes and modes, joint strength, and strains in the sectional beams. Based on the test results and observations, the following conclusions can be drawn:
1. The assembling of segments with internal tendons leads to an increase in the ductility properties of segmental beams under repeated loadings in addition to improving the shear resistance of such beams.
2. A dry joint adopted in segmental beams (SB1) was the weakest type in terms of flexural resistance. The dry joint had deflections greater than those of the reference beam by about 61% and 94% in repeated and static loading tests, respectively.
3. Mechanisms as adopted in the joint types in beams SB2 and SB3 clearly increased joint resistance to tensile bending stress as compared to the dry joint beam SB1.
4. Strengthening the dry joint by using carbon fibres as in SB3, had less effect in improving joint strength than adding epoxy to the joint (SB2). The failure modes of both types of joints occurred in the concrete adjacent to the segment interface.
5. The segmental beam formed with a multi-shear keyed joint (SB4), had the highest stiffness compared with other segmental beams and achieved the least difference in deflection readings with respect to the monolithic beam. The segmental beam SB4 had a maximum deflection about 8% higher than that of the reference beam under the repeated loading test and deflection about 16% greater than the reference beam at first crack loading.

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