COMPARISON OF BIAXIAL TENSILE BEHAVIOUR OF PLAIN AND STEEL FIBRE REINFORCED CONCRETE (SFRC) WITH DIFFERENT TESTING TECHNIQUES

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Abstract
Most concrete biaxial behaviour investigations are focused on biaxial compression due to the complexity of biaxial test set up. This paper is aimed to construct a simple and economic biaxial testing frame for conducting a biaxial tensile test on plain concrete and steel fibre reinforced concrete (SFRC). It is also aimed to compare the biaxial tensile behaviour of the current study with the previous research by using different testing techniques under an equal stress ratio. Lever arm principle is applied in the proposed biaxial test set up. For SFRC, hooked-end type steel fibre with fibre volumetric fractions 0%, 0.5%, 1.0% and 1.5% are used. Uniaxial tensile strength of plain concrete is greater than biaxial tensile strength in SFRC. For plain concrete, the opposite result is obtained. The biaxial tensile strength is insignificantly affected by the increment of fibre volumetric fraction but the post-cracking behaviour of concrete is enhanced with the inclusion of steel fibre, which is in agreement with previous findings. The comparison shows that the proposed biaxial testing technique proposed is suitable to conduct biaxial tensile test.

Keywords: Biaxial tension; Behaviour; Plain concrete; SFRC; Testing techniques

INTRODUCTION

Steel Fibre Reinforced Concrete (SFRC) is introduced since the 19th century due to its efficiency in crack bridging and ability to enhance the toughness of concrete structure. With the addition of steel fibre, concrete structures experience a more ductile failure than the catastrophic failure in normal concrete. In recent years, research on multiaxial loadings of concrete structures are gaining attention because most of the concrete structures experience multiaxial loading, such as beam-column connections, bridge decks, silos, and tunnel linings. Therefore, multiaxial loading should consider both ultimate limit state (ULS) and serviceability limit state (SLS) in the design instead of considering uniaxial loading alone (Lemnitzer et al., 2008).

Multiaxial loading can be classified into three conditions, which are biaxial compression, biaxial tension-compression and biaxial tension. From previous research, experimental data for plain concrete and SFRC are commonly available for biaxial compression and biaxial tension-compression. However, experimental data on biaxial tension of plain concrete and SFRC are very scarce. This is because the multiaxial testing setup is difficult and complex, especially for Fibre Reinforced Concrete (FRC) (Sirijaroonchai et al., 2010).
Since most concrete structures are exposed to multiaxial stresses, it is important to investigate the behaviour of concrete under biaxial stresses in constructing a systematic and reliable model for a construction design. As concrete is weak in tension, steel fibre which is added into the concrete matrix contributes to crack arresting which decelerates the formation and propagation of tensile cracks and eventually increases the concrete tensile strength. The addition of steel fibre can alter the behaviour of concrete under uniaxial tension. However, understanding the behaviour of SFRC under biaxial tension is still lacking. Therefore, it is important to investigate the behaviour of SFRC, especially under biaxial tension.

Biaxial experimental data is mostly limited to biaxial compression and biaxial tension-compression for plain concrete. The complexity to conduct the biaxial tension test, especially for FRC and the extensive cost to purchase the tri-axial testing machine, are the reasons for the limited availability of biaxial tensile experimental data. Therefore, the current study is aimed to construct a simple and economic biaxial tensile testing frame to conduct the biaxial tensile test for both plain concrete and SFRC under an equal stress ratio. This study also aimed to compare the biaxial responses from the experiments with the existing experimental data from (Abdull-Ahad and Abbas, 1989) to verify the suitability of the testing techniques.

According to previous research, there are several loading methods and testing techniques adopted by researchers to carry out the biaxial tension test on concrete, mainly on plain concrete. For the tensile loading, structural glue and epoxy adhesives are used to attach the loading platens to specimens (Hussein and Marzouk, 2000; Kupfer et al., 1969; Lee et al., 2004; Nelissen, 1972). Some researchers used casted-in-screw bars to tie with the loading platens in order to perform the tensile test (Kolle, 2006; Shang et al., 2014). Meanwhile, dog-bone shaped specimens were used to carry out tensile test under the multiaxial loading setup (Abdull-Ahad and Abbas, 1989; Shiming and Yupu, 2013).

Some pervious researchers set up multiaxial loading frame by using a simple beam and hydraulic system to control the stress ratio (Kupfer et al., 1969; Lee et al., 2004). Stress ratio is the ratio of stress exerted at minor principal to the stress exerted at major principal. The testing machine consists of two systems in which the first system is comprised of Jack 1, Jack 2 and Jack 3, while the second system is comprised of Jack 4 and Jack 5, as shown in Figure 1. Double acting hydraulic jacks are used, whereby the first system controls the stress ratio by adjusting the Jack 1 distance between Jack 2 and Jack 3, while Jack 4 and Jack 5 are connected to Jack 2 and Jack 3, respectively, in order to apply the stresses (compressive or tensile) on the specimens in the second system of the test machine.

![Figure 1. Simple beam and hydraulic system (Lee et al., 2004)](image-url)
On the other hand, (Abdull-Ahad and Abbas, 1989) constructs the biaxial tensile testing frame that is totally different from those previously discussed. The main structures of the testing frame consist of a main frame, hydraulic pump, double-acting actuators, load cell and pull equipment, which seems to be much simpler than the simple beam and hydraulic system (see Figure 2). However, there is no clear information about how to alter stress ratio.

![Figure 2. Servo-hydraulic closed-loop machine (Abdull-Ahad and Abbas, 1989)](image)

Furthermore, Kolle (2006) who investigates the biaxial behaviour of steel fibre reinforced high performance concrete (SFRHPC) states that, only a general conclusion can be obtained from the biaxial test results of Abdull-Ahad and Abbas since there are a large scatter of test points for each test series. This becomes one of the reasons in the study to compare the biaxial tensile response of plain concrete and SFRC with only equal stress ratio among the other research previously discussed. Table 1 shows a summary of the loading method and testing technique for biaxial setup among the previous research.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Tensile Loading Methods</th>
<th>Testing Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kupfer et al. (Kupfer et al., 1969)</td>
<td>Brush bearing platens with epoxy adhesives</td>
<td>Hydraulic simple beam system</td>
</tr>
<tr>
<td>Lee et al. (Lee et al., 2004)</td>
<td>Solid bearing platens with epoxy adhesives</td>
<td>Hydraulic simple beam system</td>
</tr>
<tr>
<td>Abdull-Ahad and Abbas (Abdull-Ahad and Abbas, 1989)</td>
<td>Dog-done specimen and epoxy adhesives</td>
<td>Servo-hydraulic closed-loop machine</td>
</tr>
<tr>
<td>Hussein and Marzouk (Hussein and Marzouk, 2000)</td>
<td>Brush bearing platens with epoxy adhesives</td>
<td>Servo-hydraulic closed-loop machine</td>
</tr>
<tr>
<td>Shang et al. (Shang et al., 2014)*</td>
<td>Solid/brush bearing platens with structural glue, casted-in screw bars</td>
<td>Triaxial testing machine</td>
</tr>
<tr>
<td>Ren et al. (Ren et al., 2008)*</td>
<td>Solid bearing platens with structural adhesives</td>
<td>Servo-hydraulic closed-loop machine</td>
</tr>
<tr>
<td>Kolle (Kolle, 2006)*</td>
<td>Casted-in screw Bars</td>
<td>Biaxial testing facility</td>
</tr>
<tr>
<td>Foltz et al. (Foltz et al., 2017)</td>
<td>Brush bearing platens with epoxy adhesives</td>
<td>Servo-hydraulic closed-loop machine</td>
</tr>
<tr>
<td>He et al. (He et al., 2015)</td>
<td>Solid bearing platens with epoxy adhesives</td>
<td>Triaxial testing machine</td>
</tr>
</tbody>
</table>

* Biaxial tensile test were not conducted in the experiments.

From Table 1, most research use epoxy adhesives to attach the loading platens with specimens to carry out the tensile loading, whereas for testing techniques, biaxial or triaxial testing machines promise a consistent and controlled biaxial experiments. The advantages of using a hydraulic simple beam system are that the stress ratio for both principals is consistent throughout the experiment and the setup is simpler as compared to a servo-hydraulic closed-loop machine.
EXPERIMENTAL STUDY

Specimen design

At the beginning of the planning stage, it is decided that epoxy adhesives or structural glue is used as the loading method for the biaxial tensile test. However, when the structural glue is tested, bonding failure occurs several times. Therefore, the loading method is changed to casted-in screw bars. The details of casted-in screw bars (or pull-out reinforcement) are shown in Figure 3. The specimen is designed in cruciform shape of which the overall dimension is 300 mm × 300 mm × 100 mm with an effective central area of 150 mm × 150 mm × 100 mm, as shown in Figure 4. For the specimen of uniaxial tension, the specimen design is similar to that of biaxial tension specimen but without the left and right flanges.

The manipulated parameter considered in this study is the steel fibre volumetric fractions which are 0%, 0.5%, 1.0% and 1.5%. For uniaxial tension, 3 specimens are prepared for plain concrete and SFRC with 1.5% steel fibre respectively. A total of 12 biaxial specimens are prepared for the biaxial tensile test, with 3 specimens for plain concrete as the control, and 3 specimens for each batch of SFRC mix with different fibre volumetric fractions, respectively. One of the three results from each batch is chosen for comparison based on the consistency of strength and strain data obtained among specimens.

![Figure 3. Details of steel loading platens and pull-out reinforcement](image1)

![Figure 4. Specimen design in cruciform shape for the biaxial tensile test](image2)
Material Properties

Concrete specimens are designed with characteristic strength of 40 MPa and targeted mean strength of 53.12 MPa by using water-to-cement ratio of 0.46. The amount of cement, fine and coarse aggregates for 1 m$^3$ concrete volume are 543.5 kg/m$^3$, 948.9 kg/m$^3$ and 632.6 kg/m$^3$, respectively. High range water reducing admixture is also added with a dosage of 1L/100 kg of cement to enhance the workability especially in the mix with steel fibre addition. Hooked-end type steel fibre with 60 mm in length and 0.75 mm in diameter is added last into the concrete mix. The tensile strength of the steel fibre is 1050 MPa, as given by the manufacturer.

Testing Facilities

The biaxial testing frame is set up by applying the principal of lever arm as shown in Figure 5. Rectangular hollow steel section with dimension of 150 mm height × 100 width mm × 9 mm thick is used to form the lever arm system for the major and minor principal. The end of the hollow steel section is fixed by using screw bars and connected to the steel bearing platens. The steel loading platens are designed such that the holes which located the casted-in screw bars are wider in horizontal to reduce the specimen restraint movement during testing (Figure 3).

The casted-in screw bars are first screwed to the loading platens and then to the frame. The sides which are screwed to the steel plate position on the frame reacted to the tensile loading when the load is applied. To eliminate the effects of self-weight due to Beam 1 gravity on the biaxial response during the test, the beam is rested on rollers which enables the movement for the hollow steel section end. Lubricant is applied onto the rollers to reduce friction from the beam movement.

100kN load cell is used for both major and minor principal. The load cell is placed under the actuator, in which the load obtained from the compressive force is the same as the tensile load being applied to the specimen because the distance between fulcrum and specimen is the same as the distance between actuators and fulcrum. After the specimens on the frame are set up, concrete strain gauges of 60 mm in length are lastly attached at the centre of the specimen in both horizontal and vertical directions, and perpendicular to each other to record the strain data during test.

Single-acting actuators are used to apply load during the test. Beam 1 exerts a tensile force at the major principal, while beam 2 exerts a force at minor principal. In order to achieve the same tensile load on the specimen at both major and minor principals, the distance between the specimen and fulcrum and the distance between fulcrum and hydraulic jack is fixed for both Beam 1 and Beam 2. To ensure that the load is simultaneously applied at both principals, a hydraulic jack connector is used. During testing, the load is applied every six seconds for major and minor principals to ensure a consistent loading throughout the experiment. The results obtained for plain concrete and SFRC with 1.5% fibre are then compared with the results from Abdull-Ahad and Abbas (1989) and are discussed in the following section.
RESULTS AND DISCUSSION

Compressive strength test is carried out on the 28th day with the 150 mm × 150 mm × 150 mm cube specimens. Table 2 shows the average compressive strength for plain concrete and SFRC on three cube specimens with different fibre volumetric fractions. It is obvious that with the inclusion of steel fibre, the compressive strength of SFRC is higher than plain concrete. This is due to the confinement created by steel fibre and its ability in crack bridging, resulting in the retardation of formation and propagation of cracks within the concrete matrix. Besides that, the inconsistent trend with the increment of steel fibre volumetric fraction is in agreement with the findings by previous research (Ding and Kusterle, 2000; Holschemacher et al., 2010; Lee et al., 2015; Swamy, 1974; Van Chanh, 2004; Wafa, 1990).

Table 2. Average compressive strength of plain concrete and SFRC at 28th day

<table>
<thead>
<tr>
<th>Fibre Content</th>
<th>Average Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>46.99</td>
</tr>
<tr>
<td>0.5%</td>
<td>54.09</td>
</tr>
<tr>
<td>1.0%</td>
<td>50.18</td>
</tr>
<tr>
<td>1.5%</td>
<td>56.08</td>
</tr>
</tbody>
</table>

To verify the testing frame setup in the current study, the results are compared with experimental data from Abdull-Ahad and Abbas (1989) and Lee et al. (2004). The only biaxial tensile experimental data available for SFRC is provided by Abdull-Ahad and Abbas. However, for stress-strain relation, only experimental data based on 1.5% fibre volume fraction with aspect ratio of 100, is available. Furthermore, experimental results related to stress ratio of 0.8 instead of 1.0 are the only available data from literature. Since the data is extremely limited, the results for the current study is compared with the data of plain concrete and SFRC with 1.5% fibre volume fraction and stress ratio of 0.8.

Based on Figure 6, the addition of 1.5% steel fibre does not have significant increment for both biaxial tensile strength and strain. In the current study, the results of the strength are similar with Abdull-Ahad and Abbas (1989) where the increment is insignificant. However, the strains for both plain concrete and SFRC does not differ much. As the weakest point of the specimen in current study is at the indented area, cracks are mostly initiate at that region, which upon failure, strain gauges are unable to obtain the data from the post-cracking behaviour contributed by the steel fibre.
However, through observation shown in Figure 7, it is obvious that the inclusion of steel fibre retards the propagation of cracks and eliminates the sudden failure as in plain concrete, where the concrete changes from brittle to ductile behaviour, similar to the behaviour explained by the stress-strain relation from the mentioned research.

Figure 8 illustrated the comparison of stress-strain relation between plain concrete and SFRC with 1.5% steel fibre under uniaxial tension and biaxial equal tension. It is noticed that the biaxial strength is higher than the uniaxial strength in plain concrete whereas the SFRC shows the opposite results. Kupfer et al. (1969) and Hussein and Marzouk (2000) who conduct a biaxial tensile experiment on plain concrete, conclude that the biaxial tensile strength is similar to the uniaxial strength of the concrete. However, Lee et al. (2004) obtain a smaller biaxial tensile strength than uniaxial strength of the concrete under equal stress ratio. The biaxial strength of plain concrete obtained by Abdull-Ahad and Abbas (1989) agrees with the results from Kupfer et al. (1969) and Hussein and Marzouk (2000).
Results obtained in the current study shows disagreement with the previous reported results. For plain concrete, the introduction of the transverse tensile force required the concrete matrix to withstand the forces in two directions, where it only needs to withstand one direction tensile force originally in uniaxial tension. This causes the concrete matrix to become stiffer and results in a higher failure strength. For the uniaxial tension in SFRC with 1.5% steel fibre, the crack bridging properties of steel fibre enhances the tensile strength as well as the ductility of the SFRC. Similarly with the biaxial tension in plain concrete, the concrete matrix and steel fibre requires to encounter the stresses from two directions. When the capacity of concrete matrix to withstand tensile stress is reached, cracks initiated. The stress redistribution from the concrete matrix to the steel fibre is from two directions, which decreases the failure strength of SFRC even though SFRC becomes stiffer.

Figure 9 illustrated the comparison of the normalised biaxial tensile strength for SFRC from Abdull-Ahad and Abbas (1989) with stress ratio of 0.8, together with the SFRC results obtained from this study under equal stress ratio. The testing techniques used by Abdull-Ahad and Abbas is servo-hydraulic closed-loop machine, in which plate specimens are used to conduct the biaxial tensile test. The testing techniques used in this study is the biaxial testing set up mentioned in section 3.3 which is applied to the concept of lever arm principle. The biaxial strength of SFRC is higher than the plain concrete from Abdull-Ahad and Abbas (1989), while the increase in biaxial strength of SFRC obtained from the current study is insignificant as compared to plain concrete. On the other hand, the current study obtains a similar trend with the findings from Abdull-Ahad and Abbas (1989), where the increment in steel fibre volumetric fraction does not have much contribution on the strength of concrete.

Shang et al. (2014) concludes that the mechanical behaviour of concrete under multiaxial loading is influenced by the testing techniques, testing apparatus or equipment and type of concrete, which is well-agreed through the data comparison and analysis in the current study. Furthermore, the similar trend obtained from the comparison of increment in fibre volumetric fraction on biaxial tensile strength of the concrete shows that the biaxial tensile testing frame setup is suitable in conducting the biaxial tensile test. However, to enable the collection of strain data from post-cracking after failure, it is necessary to modify the shape of the specimens to induce cracking at the effective central area where strain gauges are located.
CONCLUSION

In conclusion, the current study agrees with the experimental results from the previous research, in which the inclusion of steel fibre volumetric fraction does not have significant increment in the biaxial tensile strength of the concrete, but greatly contribute to the ductility and the concrete post-cracking behaviour. The biaxial tensile strength is reported to be similar to the uniaxial strength of the plain concrete, but in the current study, the biaxial tensile strength of plain concrete is greater than the uniaxial tensile strength of the concrete due to the stiffness induced by the introduction of transverse tensile load.

As for SFRC, the opposite observation is obtained where the biaxial tensile strength of SFRC is smaller than the uniaxial tensile strength. This is because the steel fibre, which is only required to cater with the crack formation and propagations from one direction in uniaxial tension, must redistribute the stress from two directions in the biaxial tensile loading which eventually decreases the ultimate failure strength.

Therefore, from the comparison and data analysis with previous researchers, it is concluded that the biaxial tensile testing frame setup is suitable to conduct concrete biaxial tensile testing, although the mechanical behaviour or the stress-strain responses of the concrete is quite different under different loading methods and testing techniques.

For further investigations, it is recommended to modify the shape of the specimens for biaxial tension to obtain the stress-strain response for the SFRC post-cracking behaviour. Since the addition of steel fibre is aimed to improve the post-cracking behaviour of SFRC, it is also necessary to investigate the relationship between toughness and biaxial tensile behaviour of SFRC.
ACKNOWLEDGEMENT

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NOTATIONS

PC = Plain concrete
SFRC = Steel fibre reinforced concrete
e1 = strain for major principal (beam 1)
e2 = strain for minor principal (beam 2)
\( \sigma_1 \) = strength for major principal (beam 1)
\( \sigma_2 \) = strength for minor principal (beam 2)
\( \sigma_T \) = uniaxial tensile strength of plain concrete

REFERENCES


