Behaviour of Plain Concrete and Steel Fibre Reinforced Concrete (SFRC) under Biaxial Stresses - A Review

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Abstract. This paper provides general overview on the development of biaxial behaviour of plain concrete and steel fibre reinforced concrete (SFRC) under various types of loading conditions, namely, biaxial compression, biaxial tension-compression and biaxial tension. The biaxial behaviour including failure envelope, ultimate strength, failure mode and stress-strain relationship of plain concrete and SFRC are reported and compared. The effects of fibre volumetric fraction of fibre in SFRC on the biaxial behaviour are also discussed. Overall, previous researchers show that the inclusion of fibre enhance the biaxial behaviour of the concrete, agreed with the biaxial failure envelope developed. However, further experimental works and investigation is required to determine the relationship between the biaxial behaviour of SFRC and its fracture toughness, in addition to prove the analytical prediction of biaxial behaviour of SFRC especially in biaxial tension-compression and biaxial tension.

1. Introduction

Fibre reinforced concrete (FRC) had been introduced as early as in the 19th Century and is commonly used in the construction industry in order to enhance the properties of the concrete. Many types of fibres made from different materials such as steel, glass, carbon, polyethylene, nylon, etc. are used for different purposes. For example, steel fibre, glass fibre and carbon fibre are used to enhance the structural strength of the concrete while polyethylene fibre is used to enhance the workability and reduce the shrinkage cracking. Steel fibre is the most commonly used among the other fibres especially for improving the tensile strength, flexural strength and toughness of the concrete [1-3]. The major benefit of steel fibre reinforced concrete (SFRC) is that it is excellent to “bridge” cracks and resisted the propagation of cracks before failure [4, 5]. These structural characteristics are influenced by the fibre shape, fibre volumetric ratio, fibre orientation, concrete strength and others [6-8].

Multiaxial loading is always a popular topic for construction materials as many load-carrying structures such as columns, beams and slabs are often subjected to multiaxial loading. However, only uniaxial loading is normally considered in the construction design. Hence, it is a concern to consider multiaxial loading in the construction design. As SFRC can enhance the mechanical properties of concrete, researches had been carried out to investigate the behaviour of SFRC under biaxial loading.
However, lack of understanding on biaxial behaviour of concrete and SFRC making the construction design for biaxial loading complicated.

2. General background

Entire range of biaxial loading such as biaxial compression, biaxial compression-tension, and biaxial tension are discussed in this paper. Compression and tension stresses are commonly experienced in concrete and steel structures. Under uniaxial compression, concrete usually fails due to crack formation parallel to the direction of loading. This is known as splitting failure, columnar failure or prism failure [9-13]. On the other hand, under uniaxial tension, crack normally formed perpendicular to the applied tensile load [14, 15]. However, for biaxial loading, the confinement stress exerted on the major and minor principals can alter the failure mode of the concrete.

To prepare the specimens for biaxial compression, the loading surface of the concrete plate specimen is often being finished by the attrition machine [14]. For SFRC, the concrete is usually casted in prism mould and trimmed into several plate specimens to the desired shape and size to ensure the uniform distribution of steel fibre [10]. Besides that, for the tension loading in biaxial tension-compression and biaxial tension, the most commonly used method is gluing the steel loading platens to the specimens by structural glue. The loading platens can be steel solid platens or steel brush platens. Steel brush loading platen was developed by Kupfer et al. [16] in order to minimise the restraint and friction between the loading platen and specimen. Some researchers used the friction-reducing approach, by applying lubricants between several layers of plastic membranes and placed between the loading platens and specimen to reduce friction [11, 17-20]. On the other hand, Tetrafluorethylene pads used by Ren et al. [21] and Teflon used by Lee et al. [14] were also aimed to reduce the confinement due to friction.

![Figure 1. Failure envelope for biaxial strength of concrete [16].](image)

Failure envelope is usually used to describe the biaxial behaviour of concrete. Figure 1 shows the general failure envelope for biaxial strength of concrete. For biaxial compression, the biaxial strength is
greater than the uniaxial compressive strength. This is due to the confinement stress introduced by the biaxial minor principal stress which control the development of cracks [11]. The confinement reduces the occurrence of tensile stress formed within the concrete due to Poisson’s effect [9] and thus increase the ultimate strength of concrete. Hence, the confinement stresses exerted on the specimen able to change the failure mode of concrete specimen from splitting tensile failure to shear type failure [9, 13, 19, 22]. On the other hand, biaxial compression-tension strength of concrete specimen is usually smaller than both the uniaxial compressive strength and uniaxial tensile strength [16, 17, 23]. According to Lee et al. [14], there are three types of failure patterns, which is influenced by the stress ratio. When compressive stress at the major principal is much greater than the tensile stress at the minor principal, the failure mode was similar to the failure mode under biaxial compression of which the cracks inclined to the direction of applied compressive load. Besides that, tensile cracks appeared perpendicular to the applied tensile force when the ratio of tensile load to the compressive load is larger. For biaxial tension-compression where the compressive stress is relatively small, the specimens shows failure with a major tensile crack, similar to the failure mode of uniaxial tension. Furthermore, for biaxial tension, the failure mode is also similar with the failure mode of uniaxial tension of concrete, which characterised by a major tensile crack, allocated perpendicular to the applied tensile force.

3. Comparison between plain concrete and SFRC under biaxial compression

As mentioned in Section 2, the confining pressure introduced by the biaxial loading in the minor principal alleviates the tensile stress in the concrete specimens. More strength is provided by the confining pressure to resist the failure and cracking. Hence, the biaxial strength is larger than the uniaxial strength in plain concrete. For SFRC, the inclusion of fibre improves the post-cracking behaviour of the concrete and increase the energy absorption of the concrete specimen. The steel fibres hold the concrete matrix and thus induce a passive confinement in the out-of-plane direction for the concrete under loading [24]. The confinement due to steel fibre under biaxial compression is similar to plain concrete under triaxial loading [10, 12, 25-27]. Hence, the biaxial strength for SFRC is generally greater than the biaxial strength of plain concrete.

According to Muragappan et al. [27], biaxial strength of SFRC is influenced by several factors such as fibre volume fraction, fibre aspect ratio, fibre bond strength and concrete strength. Orientation of fibres due to the direction of casting also affect the biaxial strength of the specimens [12]. Chen et al. suggested that the biaxial compressive strength is not only depends on the concrete uniaxial compressive strength, but also on the fracture toughness [18]. Yin et al., Tan et al. and Chi et al. [13, 25, 26] reported that the ultimate biaxial strength of concrete can be increased by increasing the volume fraction of the steel fibre. Tan et al. also reported that the increasing aspect ratio can improve biaxial compressive strength and failure strain although the effect is not as significant as the effect influenced by fibre volume fraction.

The failure envelope of SFRC under biaxial compressive stress is similar to plain concrete. According to Lim and Nawy, [9] although steel fibres act as a passive confinement to the specimen, they are unable to transform the failure mode from splitting tensile failure to shear type failure under uniaxial compression. However, Yin et al. and Foltz et al. concluded that the addition of fibres in concrete reinforces the concrete specimen and prevent propagation of tensile cracks, which change the failure mode from splitting tensile failure type to shear failure type [10, 26]. This indicates that the inclusion of fibre can transform the concrete specimens form brittle to ductile behaviour.

Figure 2 shows the comparison of the biaxial failure envelope of plain concrete and SFRC with different fibre volumetric ratio under biaxial compression. The properties of the steel fibre is almost the same in both research, but the uniaxial compressive strength obtained in Muragappan et al. [27] is higher than that obtained from Swaddiwudhipong et al. [28]. This is the reason of the overall biaxial compressive strength from Swaddiwudhipong et al. is higher than that of Muragappan et al. Besides that, from both the data results, we can concluded that the inclusion of fibre in SFRC and the increase of fibre
volumetric ratio greatly affect the biaxial compressive strength of the concrete. However, the inclusion of fibre does not have significant effect on the uniaxial compressive strength of the concrete specimens in Swaddiwudhipong et al. compared to the uniaxial compressive strength obtained in the study by Muragappan et al.

On the other hand, concrete stress and strain is largely depends on the stress ratio under biaxial loading [10, 28, 29]. Stress ratio is the ratio of stress applied at minor principal to that at major principal of concrete specimen. As mentioned previously, the load applied at minor principal exert an active confinement stress to the concrete specimen, which then increase the strength of the concrete. The increase in the minor principal stress increase the confinement stress of the concrete specimen [12]. For SFRC, the steel fibres enhance the postcracking behaviour of the concrete and prevent the concrete from the tensile splitting type failure at the unloaded direction, thus increase the stiffness of the material. Sirijaroonchai et al. and Muragappan et al. stated that inclusion of fibre has insignificant effect on pre-peak response of the concrete, but greatly affect the peak and post-peak response of the concrete [24, 27].

![Biaxial Failure Envelope](image)

**Figure 2.** Comparison of biaxial failure envelope between the results from Muragappan et al. [27] and Swaddiwudhipong et al. [28].

Yin et al. reported that the failure strains of SFRC increased with the increase of steel fibre volume fraction [26]. Foltz et al. also suggested that large residual strength is obtained with large compressive strain in biaxial compressive loading [10]. However, the concrete strain only increases with the increase of fibre volume fraction until the optimum dosage. This is because the high fibre volume fraction may induce more microcracks and voids between the aggregate-mortar interface which generate weakness in the concrete matrix [13]. From most of the results obtained from the previous research, the largest ultimate biaxial compressive strength usually occurs at stress ratio of 0.5 [9, 25, 27, 28, 30].

Figure 3 shows the biaxial compressive stress strain curve of concrete specimen under different biaxial stress ratio [10]. The steel fibre used in the study was hooked-end steel fibre with volumetric fraction of 1.5%. The figure shows that the inclusion of fibre has insignificant effect on the pre-cracking
behaviour of the concrete as the pre-cracking strength is almost the same under different biaxial stress ratio, respectively. However, a significant effect of ultimate strength and the residual strength had been observed under different biaxial stress ratio. The post-cracking behaviour of the concrete is improved by the increasing the stress ratio, because the confinement stress exerted on the concrete is increased with the increase of stress ratio. On the other hand, Figure 4 shows the effect of fibre volumetric fraction and the aspect ratio on the concrete strain [26]. The higher fibre aspect ratio leads to higher concrete strain. Figure 5 shows the effect on concrete strain under the combination of different stress ratio and fibre volumetric fraction [9]. The figure proves that the increase in fibre volumetric fraction enhanced the concrete strain by providing more confining stress according to the fibre dosage. The highest ultimate biaxial strength is achieved at stress ratio of 0.5.

Figure 3. Biaxial compressive response of plain concrete and high performance fibre reinforced cementitious composites (HPFRCC) under different stress ratio [10].

Figure 4. Stress-strain relationship under biaxial compression with stress ratio = 1.0 [26].
Figure 5. Stress-strain curves of plain and SFRC of different fibre volumetric fraction under stress ratio of 0.5 and 1.0 respectively [9].

4. Comparison between plain concrete and SFRC under biaxial tension-compression

Besides biaxial compression, load bearing structures also experience biaxial tension-compression. The introduction of external tensile force on the concrete structure will decrease the ultimate strength of the concrete. Hence, it is important to take attention on the behaviour of concrete under biaxial tension-compression in structural design. According to Shang et al. [17], several factors are to be considered which affect the mechanical behaviour of concrete under biaxial tension-compression: concrete strength, testing apparatus, testing and measuring techniques including the type of loading platens, applied mode of tensile load, and method to reduce the friction between the specimen and loading platen.

From the previous researches, the ultimate biaxial strength of concrete under biaxial tension-compression is smaller than both uniaxial compressive strength and uniaxial tensile strength [16, 31-33]. This is because the extra force loaded in the opposite direction at the minor principal of concrete specimen encourages the growth of microcracks perpendicular to the tensile load applied of which will weaken the concrete matrix. This causes the decrease in the ultimate strength of concrete. The failure mode of concrete under biaxial tension-compression had been discussed in Section 2. According to Kupfer et al. [16], the behaviour of concrete specimen under biaxial tension-compression is similar to that of uniaxial compression, as long as the tensile stress exerted is smaller than 1/15 of the concrete compressive stress. For larger applied tensile stress, the concrete specimen tends to behave similar to the one under uniaxial tension. This is suggested to be a transition zone for concrete specimen from uniaxial compression to uniaxial tension. Wastiels [32] stated that the crack propagation, failure mode, and stress-strain relation are similar to the uniaxial compression under smaller tensile load; while the biaxial behaviour is similar to the uniaxial tension under larger tensile load, which is also in agreement with Kupfer et al.

The stress-strain response of the concrete depends on the stress ratio, similar to that under biaxial compression. When the absolute stress ratio increases, the lateral tensile stress increases and causes the ultimate compressive strain decreases [15]. This is due to the formation of microcracks in the brittle material when lateral tensile stress is applied, causes the decreasing of concrete stiffness. Normally, under uniaxial compression, the concrete will experience splitting tensile type failure due to Poisson’s effect. However, the introduction of lateral tensile stress reduces the tensile strain at failure and decrease the strength of concrete to resist the failure. Figure 6 shows that the increase of absolute stress ratio due to the increasing of tensile stress reduces both the compressive strain and tensile strain of the concrete. Hence, the biaxial tension-compressoin strength of concrete is smaller than both the uniaxial
compression and uniaxial tension. This indicates that the concrete specimens can withstand higher indirect tensile stress compared to the direct tensile stress [14].

**Figure 6.** Stress-strain relationship for concrete under biaxial tension-compression by Lee et al. [14] and Wang and Song [20] respectively.

For SFRC, there is limited information and experimental data for the biaxial tension-compression from the past researches. However, from the proposed failure envelopes by Hu et al. [34] as shown in Figure 7, the increase of volumetric fraction will increase the biaxial tension-compression strength of the concrete. The prediction is reasonable as steel fibres help in bridge cracking, are able to resist the concrete to fail in tensile. This will increase the strength of the concrete although the biaxial strength is still smaller than the corresponding uniaxial tensile and uniaxial compression strength.

**Figure 7.** Proposed failure envelope for fibre reinforced concrete [34].

5. Biaxial Tension

The behaviour of concrete under biaxial tension is similar to uniaxial tension and does not depends on stress ratio [14, 16, 32]. However, according to Hussein and Marzouk [33], there is a small increase in the biaxial tensile strength of concrete when the biaxial tensile stress ratio is equal to 1, which is different from other researchers mentioned above. However, Hussein and Marzouk stated that the difference is insignificant that there is not essential to have an accurate verification. When the concrete fails under biaxial tension, the apparent tensile crack usually occurs at the location perpendicular to the direction of loading with the largest stress [32]. Lee et al. [14] obtained the result different from the situation mentioned earlier. Under biaxial tensile loading, major inclined crack is developed to the largest
principal stress. On the other hand, for the stress-strain response of concrete under biaxial tension, Hussein and Marzouk [33] stated that the variation of ultimate tensile strain is insignificant under different stress ratio. This proves that the biaxial tensile behaviour of concrete is independent on stress ratio.

For SFRC, there is limited data and information on the biaxial tension. However, a prediction can be made in biaxial tension-compression. Since the fibre is excellent in enhancing the tensile strength of concrete, therefore biaxial tension behaviour is similar to uniaxial tension. It can also be suggested that the behaviour of biaxial tension of SFRC in ultimate strength and the capacity of resisting cracks are more advanced than plain concrete.

6. Conclusion
Generally, the biaxial failure envelope is agreed by the researches in the literature. There is a number of researches on the inclusion of fibre under biaxial compression but limited experimental data of inclusion of fibre in concrete under biaxial tension-compression and biaxial tension. Besides that, there is limited information of the effects of other factors which influence the biaxial behaviour of concrete such as the fibre aspect ratio, the concrete strength of SFRC and the orientation of the fibre. The discrepancies of results among the researches are due to the difference in loading machine used, testing techniques, friction reducing method and the loading path. This can be concluded that no well-established testing procedure to determine the biaxial behaviour of concrete. Apart from that, there is also a lack of compilation of data for the biaxial behaviour of SFRC under all the loading conditions from the published test results. Further experimental work and investigation is required to prove the prediction of the biaxial behaviour of different types of concrete including SFRC especially under biaxial tension-compression and biaxial tension. Besides that, close attention on fracture toughness of SFRC is needed for the further investigation, since the SFRC biaxial behaviour is not only depends on the uniaxial strength of the concrete but also the fracture toughness of the concrete.

Overall, the inclusion of steel fibre in concrete enhance the biaxial behaviour of SFRC compared with plain concrete. However, the concrete biaxial behaviour also greatly depends on the applied stress ratio.

7. References
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