BEHAVIOR OF STEEL FIBRE REINFORCED CONCRETE IN COMPRESSION

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ABSTRACT

Standard compression tests are conducted on concrete cylinders made with concrete having different amount of steel fibres to investigate compression behaviour of steel fibre reinforced concrete. The effect of volumetric ratio of steel fibres on compressive strength, corresponding peak strain and the compressive stress-strain curve is explored. The test results show that the more the amount of fibres the higher the compressive strain the cylinder can sustain. It is also observed that both compressive strength and the strain corresponding to the peak stress increase with the addition of steel fibres. Interrelationships relating the compressive strength and the corresponding peak strain with the volumetric ratio of steel fibres are established based on the test results. The experimental result also shows that if the compressive stress and strain are normalized with respect to the compressive strength and the peak strain respectively, the resulting normalized stress-strain curves lie close to each other and are not influenced by the fibre content. An equation to represent this unique relationship between the normalized compressive stress and strain is also proposed and verified.

KEYWORDS

Steel fibre reinforced concrete (SFRC); plain concrete; fibre content; compression; normalized stress-strain relationship; compressive strength; peak strain; post-peak softening

INTRODUCTION

Concrete with steel fibres is proved to have better compression behaviour than plain concrete. The maximum compressive strain, which is assumed as 0.003~0.0035 for plain concrete is likely to be higher for steel fibre reinforced concrete (SFRC). Also, the post-peak softening branch of the compressive stress-strain curve of SFRC is expected to be flatter than that of plain concrete; i.e. the stress in the post-peak range is higher in SFRC. Obviously, constitutive equations representing the compressive stress-strain relationship of plain concrete cannot capture the stress-strain curves of SFRC. Not only the stress-strain curves and the equations representing these curves differ between SFRC and plain concrete, but they also differ between SFRC with different amount of steel fibres. Hence, generalized equations that take into account the fibre content are needed if the compressive stress and corresponding force carried by SFRC with a given fibre content are to be calculated accurately.

Test results on mortar with steel fibres have shown that the addition of fibres lead to increases in compressive strength and the strain at peak stress [Fanella and Naaman 1985]. Some studies have been done to investigate the effect of fibre content on the post-peak softening branch of the compressive stress-strain curve of SFRC [Hughes and Fattuhi 1977]. Fanella and Naaman [1985] found that an increase in the volumetric ratio of steel fibres leads to a relatively flatter post-peak softening branch in the stress-strain curve of mortar with steel fibres. Only a few attempts have been made to establish constitutive equations for SFRC [Ezeldin and Balaguru 1992], and no studies in the authors' knowledge have led to generalized constitutive equations taking into account the fibre type and fibre content. The main objective of this paper is to investigate the compressive behaviour of SFRC with different fibre content and to explore generalized interrelationships between fibre content and the compression stress-stress curve parameters; mainly the compressive strength and the peak strain.

EXPERIMENT DETAILS

Standard cylinders of 100 mm diameter and 200 mm height were made of concrete with different fibre content. Six sets of twelve SFRC cylinders having 0%, 0.5%, 1.0% (two sets for two different types of fibre), 1.5% and 2.0% steel fibres (by volume) were prepared. The second and the third sets included 1.0% steel fibres of two different types commonly used in New Zealand, namely Dramix fibres [www.bekaert.com] and Novotex fibres [www.novocon.com]. This was aimed to see if the different types of steel fibres used in New Zealand had a significant effect on the compression behaviour of SFRC in general. In the other sets having 0.5%, 1.5% and 2% fibre content, Novotex fibres were used. The properties of these fibres used in the specimens are shown in Table 1.

The specimens were prepared with concrete in six different batches. Ready-mix plain concrete was ordered and the weight of the steel fibres calculated to obtain the prescribed volumetric ratio was added to the concrete and mixed in the truck for another 30-40 revolutions to ensure the homogeneity of the mix. Plasticizer was added to enhance the workability of the mixes; especially the last batch with 2% steel fibres by volume was very difficult to work on.

Table 1 Steel fibre technical specification

	Novotex fibre FE0730	Dramix fibre RC65/35BN
Fibre Length	30 mm	35 mm
Equivalent Diameter	0.7 mm	0.55 mm
Aspect Ratio	43	64
Tensile Strength	1150 MPa	1100 MPa
End Type	Flattened ends with round shaft	Hooked ends

The first batch (P1) was plain concrete without any fibres (i.e. 0% fibre content), and 12 cylinders were made from this batch. The second batch (P2) was prepared and mixed with 1% (by volume) Dramix RC65/35BN steel fibres, whereas the remaining four batches (namely P3, P2, P4, P6 and P5 respectively) were mixed with Novotex FE0730 steel fibres ranging from 05% to 2% by volume with an increment of 0.5%. From the five SFRC batches (P2, P3, P4, P5 and P6), six cylinders were made with the plain concrete before adding the steel fibres and the other six cylinders were made after mixing the fibres.

All cylinders were wet cured in a 20^0C fog room for 28 days. The cylinders were covered with plastic sheets throughout the curing period to reduce the amount of water evaporation. An AVERY 7104 DCJ Compression and Tension testing machine with a capacity of 1000 KN was used for the compression tests. The compression load was applied at a rate of 0.15 MPa per second following ASTM standard [ASTM C39/C39M-01]. In order to avoid friction that would otherwise alter the failure plane and also the measured load to some extent, a thin layer of lubricant sandwiched between two Teflon sheets was used between the loading plate and the two end surfaces of the cylinders. A high speed data logger was used to record the axial load and the corresponding deformation.

RESULTS AND DISCUSSION

General Features of Compression Stress-Strain Curves

The axial load applied to the cylinders was recorded through the actuator, and the axial deformation was measured by two potentiometers stuck on two diametrically opposite sides of each cylinder. The recorded load was divided by the initial cross-section area of the cylinders to obtain the axial compressive stress and the axial deformation was divided by the gauge length (length covered by the potentiometer) to obtain the axial compressive strain. Thus derived axial stresses for different specimens in one set are averaged and plotted against the axial strain for the six different mixes in Figure 1.

As can be seen in the figure, the cylinders made of plain concrete and those having 0.5% fibre content failed in a brittle manner soon after crossing the peak strength, and the post-peak softening branch of stress-strain curves of these cylinders could not be captured. For other batches with fibre content more than 0.5%, the cylinders could be compressed without failure until the axial strain exceeded 2%, and the average stress-strain curves of these specimens clearly showed a stable post-peak softening branch. In stark contrast, the plain concrete cylinders made of the same batch of concrete before adding and mixing the fibres failed before the axial strain reached 0.5%, thereby clearly suggesting that the addition of fibres enhanced the deformability of the concrete.

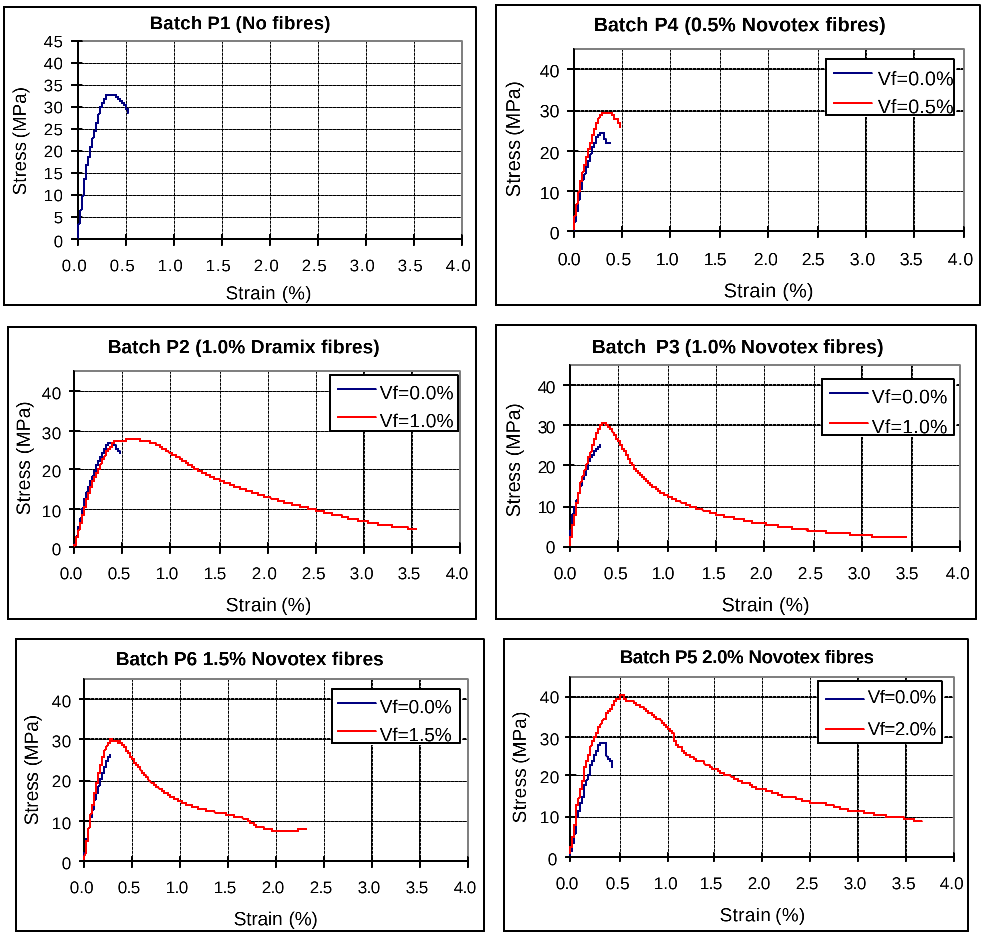

Figure 1 Average compressive stress-strain curves of SFRC with different fibre content

The average value of compressive strength and the axial strain corresponding to the peak stress (referred to as *peak strain* hereafter) for the plain concrete and SFRC cylinders in different batches are listed in Table 2. Although the compressive strength of plain concrete before adding and mixing the steel fibres varied considerably across different batches, the compressive strength of the SFRC cylinders was in all batches higher than that of the plain concrete cylinders made from the same batch. The peak strain of the plain concrete in different batches varied between 0.27-0.38%; these are likely to have been overestimated as they include the strain due to the effect of creep and shrinkage. The peak strain was also found to be larger in SFRC cylinders than in plain concrete cylinders in all batches.

Table 2 Compression strength and peak strain

Series	P1	P4		P2		P3		P6		P5	
V_f (%)	0	0.5	0	1.0	0	1.0	0	1.5	0	2.0	0
Mean f'_c	33.2	30.7	25.5	29.7	27.0	30.8	28.7	31.1	25.6	41.2	28.8
Mean e_{peak}	.0036	.0036	.0030	.0056	.0038	.0036	.0032	.0034	.0027	.0057	.0033

As shown in Figure 1, the stress-strain curves for the SFRC cylinders in batches P2 and P3 are noticeably different, although the corresponding curves of the plain concrete cylinders in these batches look similar except for a small difference in the compressive strength. The addition of Dramix fibres did not enhance the compressive strength but caused a significant increase in the peak strain and the rate of decrease of compressive stress in the post-peak range was smaller. On the other hand, a substantial increase in compressive strength was achieved with the addition of 1% Novotex fibres in batch 3, but the peak strain did not increase much and the rate of reduction of compressive stress in the post-peak range was higher. This indicates that Dramix fibres can sustain larger compressive strain than Novotex fibres before the stress drops to a prescribed permissible limit.

Normalized compression stress-strain curves

Next, the absolute values of compressive stress and strain are divided by the compressive strength and the peak strain, respectively. Figure 2 presents the average normalized compressive stress-strain curves for the P1 series (plain concrete cylinders) and other four series including the Novotex fibres (i.e. P3, P4, P5 and P6). Despite the apparently different absolute stress-strain curves in Figure 1, the normalized stress-strain curves for the different batches are very close to each other and do not indicate any correlation with the fibre content except that the normalized curves terminate early (before the normalized strain equals 2) for SFRC with fibre content less than or equal to 0.5%.

In fact, the normalized stress-strain curve for batch P2 (with 1% Dramix fibres), if plotted in Figure 2, would also lie within the narrow band yielded by the five curves. This also indicates that the normalized stress-strain curves are not dependent on the fibre type as well. This is a very useful piece of information which makes the mathematical formulation of compressive stress-strain relationship of SFRC a lot easier.

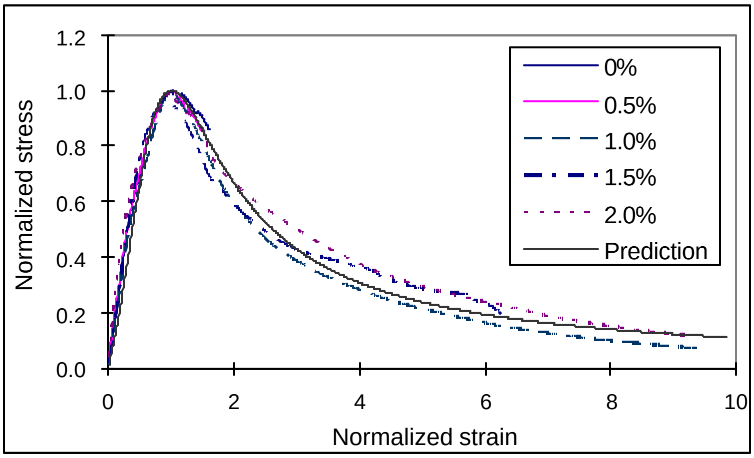

Figure 2 Normalized compression stress-strain curves of SFRC with different fibre content

MODELING OF COMPRESSION BEHAVIOR OF SFRC

Earlier discussions have established that the quality and amount of steel fibres affect the compressive stress-strain behaviour of concrete but the normalized stress-strain curves remain unaffected by these variables. Hence, a common equation interrelating normalized compressive stress with the normalized compressive strain is enough for SFRC with any type and quantity of fibres. Furthermore, if the average compressive strength and the peak strain of SFRC with a given quality and quantity of fibres are known, the normalized stress-strain relationship can easily be used to generate the absolute compressive stress-strain curves.

As a robust mix design of SFRC is not yet available; at least not known to the authors; treating the compressive strength and peak strain of SFRC as the base variables in the model makes little sense. Nevertheless, the compressive strength and peak strain of plain concrete before adding and mixing the steel fibres can be set as the primary variables as there are well-established mix design methods to generate a given compressive strength, and the peak strain of plain concrete is a dependent variable of its compressive strength. Hence, the compressive strength and the peak strain of SFRC need to be expressed in terms of the compressive strength and peak strain of plain concrete to supplement the normalized compressive stress-strain relationship.

Compression strength and peak strain of SFRC

As explained earlier, the steel fibres' quality and content influence the compressive strength and peak strain of the SFRC. As most of the SFRC cylinders tested were made of Novotex fibres and only a few samples had Dramix fibres, accurately modelling the effect of fibre quality on the compressive strength and peak strain of SFRC is out of scope of this study. The effect of volumetric ratio of fibres on the compressive stress and peak strain is modelled based on the test results here.

The ratio of compressive strength of the SFRC cylinders in different batches to the average compressive strength of plain concrete cylinders made from the same batch (before adding and mixing the steel fibres) is shown in Figure 3a. As can be seen, the compressive strength of SFRC normalized with respect to that of plain concrete increases with an increase in fibre content. Although there is substantial variation in the results of different specimens tested with the same fibre content, a straight line (see Figure 3a) qualitatively represents the dependency of the normalized compressive strength to the fibre content. The linear equation representing this straight line, which describes the interrelationship between the volumetric ratio of fibres (V_f) and the normalized compressive strength ($f_{peak}/f_c^{'}$), is given as:

$$\frac{f_{peak}}{f_c^{'}} = 1 + 20\,a_f V_f \qquad (1)$$

where, V_f is the volumetric ratio of steel fibres and a_f is an experimental constant taking into account the quality/type of fibres. The value of a_f is 1 for Novotex fibres and its value needs to be calibrated before using for other types of steel fibres. For example, a_f = 0.5 calibrates with the results of tested SFRC cylinders with 1% Dramix fibres.

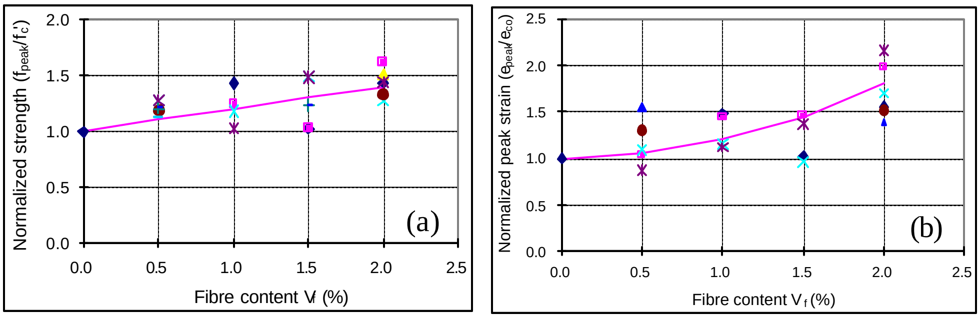

Figure 3 Variation of normalized compressive strength and peak strain with fibre content

The ratio of peak strain of SFRC to the peak strain of plain concrete before adding and mixing the steel fibres for different specimens in different batches is plotted against the fibre content in Figure 3b. As expected, the normalized peak strain increases with an increase in fibre content. Although there is substantial scatter among the specimens having the same fibre content, a quadratic equation given in Equation 2 below qualitatively captures the increasing trend of the normalized peak strain with an increase in fibre content.

$$\frac{e_{peak}}{e_{co}} = 1 + 2000\,a_e V_f^2 \qquad (2)$$

in which, e_{co} is the peak strain of plain concrete and a_e is an experimental constant taking into account the quality/type of fibres. For Novotex fibres, a_e = 1 and its value needs to be calibrated before using for other types of steel fibres. For example, a_e = 2.4 approximately fits the tests results of SFRC cylinders with 1% Dramix fibres.

Normalized compressive stress-strain relationship

As suggested by the test results, the interrelationship between the compressive stress normalized with respect to the peak stress and the strain normalized with respect to the peak strain is independent of the fibre type and content. Of course, variation within a narrow band was observed, but the curves did not show any consistent correlation with the fibre content. Hence, only one curve passing through the centre of the narrow band can be used to represent the behaviour of SFRC with any type and amount of steel fibres. An equation to represent such a curve is given below:

$$s_n = \frac{e_n}{1 - e_n + e_n^2} \tag{3}$$

in which, s_n is the normalized compressive stress given by s/f_{peak} (where s is the absolute compressive stress and f_{peak} is the compressive strength of the SFRC to be calculated using Equation 1, and e_n is the normalized compressive strain given by e/e_{peak} (where e is the absolute compressive strain and e_{peak} is the peak strain of the SFRC to be calculated using Equation 2). The normalized stress-strain relationship described by Equation 3, when combined with the estimation of compressive strength (Equation 1) and peak strain (Equation 2) of SFRC, completes the compression model of SFRC. The proposed equations can be applied to any fibre type and content, only the constants a_f and a_e (in Equations 1 and 2) need to be experimentally calibrated for the fibre type.

VERIFICATION

The proposed model is verified by comparing with the test results. First, the normalized compressive stress-strain relationship (Equation 3) is compared with the normalized average stress-strain curves obtained from the tests for different fibre content. These curves are plotted together with the model prediction in Figure 2. As can be seen, the model prediction falls within the narrow band created by the experimental curves for various fibre contents.

Next in Figure 4, the absolute stress-strain curves of some cylinders with different fibre content obtained from the tests are compared with the stress strain curves predicted by using Equation 3 together with Equations 1 and 2. As the test results used for this comparison had Novotex fibres, the values of a_f and a_e in Equations 1 and 2 are set to unity. The comparison shows that the proposed model can fairly capture the compressive stress-strain relationship of SFRC with different fibre content.

Not all specimens tested are shown in the comparison and some of the tested cylinders gave stress-strain curves that deviated substantially from the model predictions. A closer scrutiny revealed that the discrepancy originated from the fact that Equations 1 and 2 did not accurately cover the scatter of the normalized compressive strength and normalized peak strain (see Figures 3a and 3b), and hence yielded values far from those suggested by the test results of some specimens. It is found that the normalized stress-strain relationship proposed in Equation 3 did not contribute any significant proportion of the discrepancy in these specimens. Had the normalized strength and peak strain been used directly from the corresponding test results, the absolute stress-strain curves obtained by using Equation 3 would be very close to the corresponding experimental stress-strain curves.

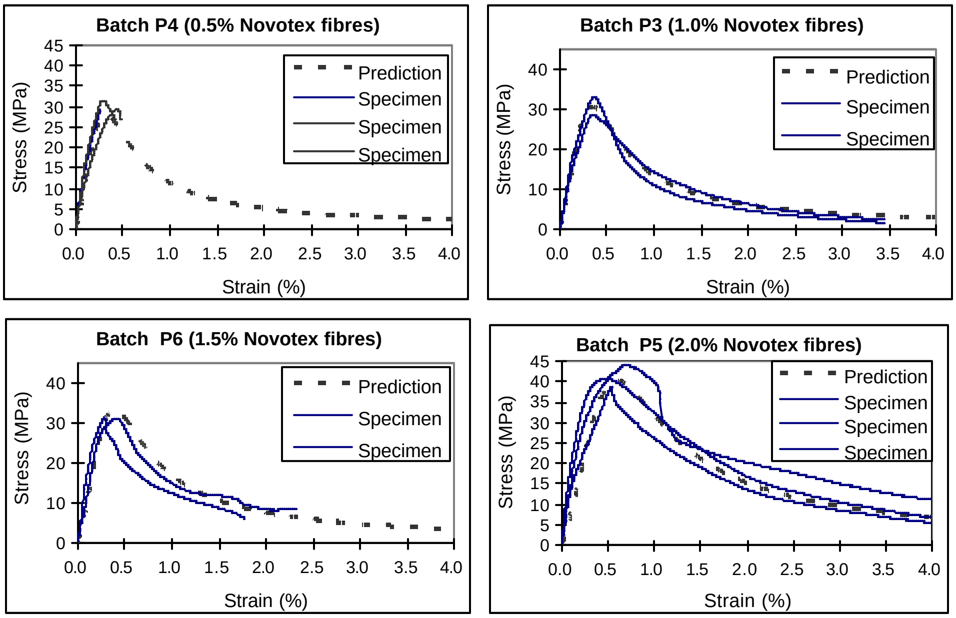

Figure 4 Comparison of the test results with the proposed model

It indicates that more work needs to be done; especially to establish more robust interrelationship between the normalized strength and peak strain of SFRC. More tests with different fibre content need to be conducted to get reliable data to clarify the valid range of normalized strength and peak strain, and Equations 1 and 2 could be modified accordingly, if needed. More tests are also to be conducted for different fibre types to see if the linear and quadratic assumptions of Equations 1 and 2 follow the trend in other types of steel fibres. These tests will also help to check the robustness of Equation 3.

CONCLUSIONS

Standard cylinders made of steel fibre reinforced concrete with different amount of Novotex fibres (ranging from 0.5% to 2.0% by volume) were tested under axial compression. The influence of fibre content on the compressive strength, corresponding peak strain and the shape of the stress-strain curves were investigated. Based on the data obtained from the compression tests of these SFRC cylinders, an analytical constitutive model is developed to predict the complete stress-strain curve of SFRC in monotonic compression. The following conclusions can be drawn from the outcome of this study:

1. Adding steel fibres in concrete changes the basic characteristics of its compressive stress-strain curve. The compressive strength of SFRC is higher than that of plain concrete; the peak strain is higher in SFRC than in plain concrete; SFRC can sustain larger compressive strain before crushing; and the compressive stress reduction in the post-peak softening branch of the stress-strain curve is milder in SFRC.
2. SFRC having 0.5% volumetric fibre content or less does not improve the compression deformability and will fail soon after reaching the peak, as in normal concrete. It is only for SFRC with fibre content above 0.5% that the compressive strain in excess of 2% could be applied to the cylinders before crushing.
3. The normalized compressive strength of SFRC (i.e. ratio of compression strength of SFRC to that of plain concrete) increases when volumetric fraction of steel fibres is increased, and the interrelationship can be described by a linear equation (Equation 1).
4. The normalized peak strain of SFRC (i.e. ratio of the peak strain of SFRC to that of plain concrete) also increases when volumetric fraction of steel fibres is increased and the interrelationship can be captured by a quadratic equation (Equation 2).
5. Although Equations 1 and 2 are derived from the compression test results of SFRC cylinders with Novotex and Dramix fibres, they can also be used for other types of steel fibres by calibrating the experimental constants a_f and a_e in Equations 1 and 2, respectively.
6. Fibre content and type affect the absolute compressive stress-strain curves of SFRC, but the normalized compressive stress-strain curves (plots of stress and strain normalized with respect to the compressive strength and peak strain respectively) lie within a narrow band regardless of the quality and quantity of steel fibres.
7. A generalized equation (Equation 3) to represent the unique normalized compressive stress-strain relationship of SFRC is proposed and verified. This equation can be used in conjunction with Equations 1 and 2 to predict the stress-strain curves of SFRC with any type and amount of steel fibres.

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