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# STEEL- FIBRE-REINFORCED CONCRETE BEAMS UNDER CYCLIC LOADS

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**Keywords:** steel fibres, finite-elements analysis, cyclic loads, shear resistance.

**Summary:** *The work presented herein is aimed at examining the potential benefits of steel fibres in concrete design. In particular, the shear behaviour of steel-fibre-reinforced concrete (SFRC) beams under cyclic loading was investigated by means of Non-linear Finite-Element Analysis (NLFEA). A key issue assessed is whether the use of steel fibres can result in a significant reduction in conventional reinforcement without compromising ductility and strength requirements. In this respect, the spacing between shear links was relaxed while steel fibres were added to see whether or not the loss of shear strength can be compensated for in this way. This is particularly useful in situations where the shear reinforcement required can lead to congestion of shear links, for instance in seismic design (the critical factor in the latter is the cyclic nature of the load, which is examined in the present research work). The numerical model was calibrated against existing experimental data to ensure the reliability of its predictions. Parametric studies were subsequently carried out using the full practical range of steel fibre dosages. Statically indeterminate SFRC beams were considered (under both monotonic and cyclic loadings) with increased spacing between shear links. Most of SFRC specimens studied in the literature are focused on determinate beams and information on statically indeterminate beams is sparse. Both axial and transverse loads have been considered which allows for the study of column behaviour as well. The investigations provided insight into how the steel fibres can help reduce the amount of conventional shear links.*

## 1 INTRODUCTION

Steel fibres are known to enhance the ductility of what is otherwise a brittle plain-concrete material [1,2]. This is useful to avoid brittle modes of collapse such as shear failure. Furthermore, improvements to ductility and energy dissipation are particularly beneficial for structures under seismic loading. Nevertheless, there is a clear gap in the literature on the application of steel-fibre-reinforced concrete (SFRC) constitutive models to study the potential of utilising SFRC to enhance the seismic – and thus cyclic – response of a structure and to assess the potential ductility and energy absorption capacity of such composites. To this end, the work presented in this article aims to examine the structural response of SFRC beams under cyclic loads using Non-linear Finite-Element Analysis (NLFEA). The beam case studies considered have already been examined experimentally [3] and thus the accuracy of the NLFEA predictions can be readily ascertained. The experiments examined only a limited range of parameters (e.g. one or two fibre contents were considered). The NLFEA have allowed for this to be extended to cover the full range of fibre volume fractions ( $V_f$ ) and therefore yields

more generic conclusions than those obtained from experimental investigations alone.

Initially, a critical review of available test data was carried out in order to assess the effect of the use of steel fibres on the material properties of structural concrete [4,5]. As part of this, a comprehensive survey was also carried out to collate and investigate the reliability of different constitutive models proposed for the numerical modelling of SFRC. Based on the findings of these studies and associated numerical calibration work, a suitable constitutive model was selected for the current study on beams. The model was implemented into a well known commercial NLFEA package (ABAQUS [6]). Further calibration work was carried out using available sets of experimental data on beams and good correlation was established between numerical and test results [4,5].

Subsequently, parametric studies were carried out using NLFEA to investigate the cyclic behaviour of SFRC beams. Statically indeterminate SFRC specimens (which have been rarely studied so far) were examined with the full practical range of fibre dosages considered and with reduced spacing between the shear links. Conclusions were thus made on the potential for fibres to compensate for reduction in shear links. The studies also helped improve understanding of how steel fibres can help enhance the energy dissipation, which is crucial in seismic design.

## 2 METHOD ADOPTED

The structural response of SFRC elements is characterised by its tensile post-cracking behaviour. The effect of the steel fibres is directly modelled into the existing concrete material model employed by ABAQUS [6] to describe its nonlinear behaviour. This is achieved by appropriately modifying the stress-strain relationship of plain concrete in uniaxial tension to enhance its strain-softening characteristics. A summary of the method adopted in the present study is summarised next.

### 2.1 Constitutive Model for SFRC

Based on the available published test data, the introduction of steel-fibres into the concrete mix predominantly results in an increase in tensile and flexural strengths [1,2]. It is important to point out that there is considerable scatter that characterizes the available test data. Apart from the obvious parameters that affect the strength of plain concrete (i.e. the water/cement ratio), the exhibited scatter can be also attributed to a wide range of parameters linked to the steel fibre used (i.e. the fibre length, the aspect ratio between the length and the diameter of the fibre, the volume fraction of the fibres as well as their shape, end arrangement – e.g. hooked or straight – and strength).

A number of available constitutive models for SFRC (that describe its uniaxial tensile stress-strain relationship) have been identified such as those proposed by [1,7-11]. The main characteristics of the models have been closely studied and subsequent calibration work was undertaken by [4,5] to investigate these models. It was concluded that the model proposed by Lok and Xiao (1999) [11] is more suitable to be adopted for the subsequent parametric studies on SFRC under cyclic conditions (the model is depicted schematically in Figure 1, with the full parameters defined elsewhere [11]).

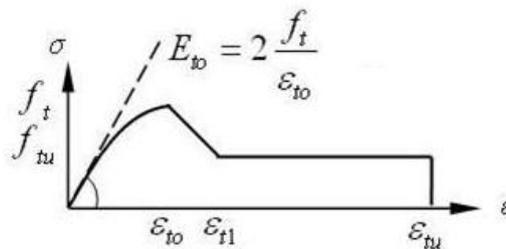


Figure 1: Lok and Xiao [11]: SFRC model in uni-axial tension

## 2.2 ABAQUS Model for SFRC

The material model adopted by ABAQUS to describe concrete behaviour is the “brittle cracking model”, which is available in ABAQUS/Explicit [6]. This model is designed for cases in which the material behaviour is dominated by tensile cracking as is normally the case for structural concrete. Thus the uniaxial stress-strain relation in compression is simply assumed to be linear elastic throughout the loading history. The behaviour of concrete in tension (prior to cracking) is also assumed to be linear elastic. However, the post-cracking phase is described using “tension-stiffening”, which allows the uniaxial stress-strain relation to be defined. A smeared crack approach is adopted to model the cracking process that concrete undergoes. For purposes of crack detection, a simple Rankine criterion is used to detect crack initiation (i.e. a crack forms when the maximum principal tensile stress exceeds the specified tensile strength of concrete). As soon as the Rankine criterion for crack formation is met, a crack is assumed to form. The crack surface is taken to be normal to the direction of the maximum tensile principal stress. Subsequent cracks may form with their surface orthogonal to the directions of any existing crack surface at the same point. Crack closing and reopening is allowed for (i.e. cracks can close completely when the stress across them becomes compressive). The crack opening and closing capability is of paramount importance for accurate modelling of concrete under cyclic conditions.

In the present study, the concrete medium is modelled by using a dense mesh of 8-node brick elements; the element formulation adopts a reduced integration scheme to avoid numerical problems due to locking. One-dimensional truss bar elements representing the steel reinforcement were placed to mimic the actual arrangement in the specimens modelled (e.g. cover allowed for). Steel constitutive behaviour follows a simple bilinear hardening model that follows Eurocode 2 [12].

## 2.3 Case Studies Considered

The SFRC continuous beams investigated numerically in the present study were initially examined experimentally by Kotsovos et al. [3] under both monotonic and cyclic load conditions. The statically-indeterminate arrangement allows for a study of the effect of fibres on strength, ductility as well as moment redistribution and formation of plastic hinges. Most of SFRC specimens studied in the literature are focused on statically determinate (namely simply-supported) beams and information on statically indeterminate beams is sparse. The salient features of the beam specimens studied are depicted in Figure 2. The specimens were loaded with an axial force (N) first, with N being equal to about 20% of the maximum value of N that can be sustained in pure compression. The axial load was applied to extend the investigation to include not only beams, but also the general case of a column under both gravity and lateral loads (e.g. under seismic action). Subsequently a lateral load (P) was applied at the middle of the larger span of the specimen and increased to failure either monotonically on some specimens or in reversed cycles on others.

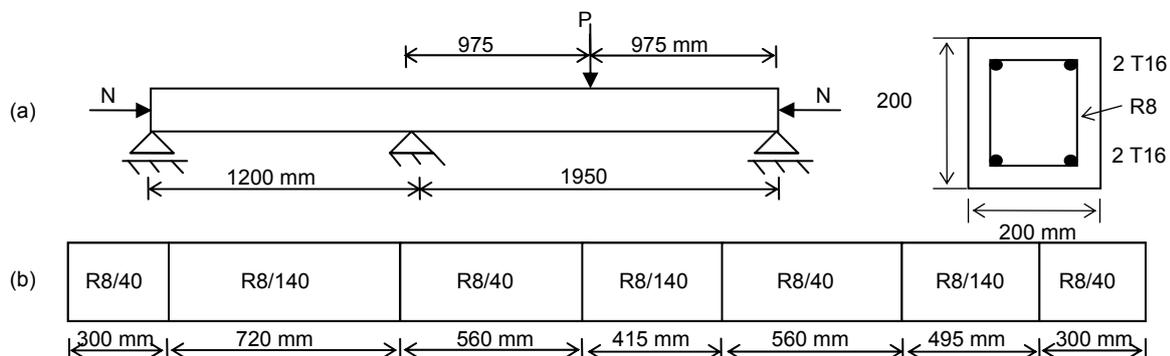


Figure 2: Schematic representation of specimen arrangements for experimental work by Kotsovos et al [3]: (a) key dimensions and (b) details of shear links

The uni-axial compressive cylinder strength of the concrete tested is approximately 37 MPa. In addition, the longitudinal reinforcement used has a 16 mm diameter with a yield stress of 556 MPa, whilst 8 mm diameter bars were used as transverse (i.e. shear) reinforcement with a yield stress of 471 MPa. Both type of steel reinforcement have an elasticity modulus of 200 GPa.

The details of the shear links are also depicted in Figure 2b. The SFRC specimens were tested with a fibre volume fraction of  $V_f = 0.4\%$ . In the numerical study currently presented, the spacing between the links was increased by 50% and 100% while  $V_f$  was increased to 1%, 1.5%, 2% and 2.5%. This allowed for investigating the effect of fibre content and its potential in compensating for reduction in shear links. This is useful in situations where shear links are needed in significant amounts (e.g. in seismic design) leading to congestion and practical difficulties in placing the links.

### 3 MONOTONIC-LOAD CASE

For both monotonic and cyclic loading cases, first a comparison was carried out with experimental data followed by a parametric study encompassing the full practical range of fibre contents.

#### 3.1 Calibration using experimental data

The load-deflection curve from the experiments was compared with the corresponding NLFEA-based predictions using ABAQUS as depicted in Figure 3a. The results show reasonable agreement with experimental data.

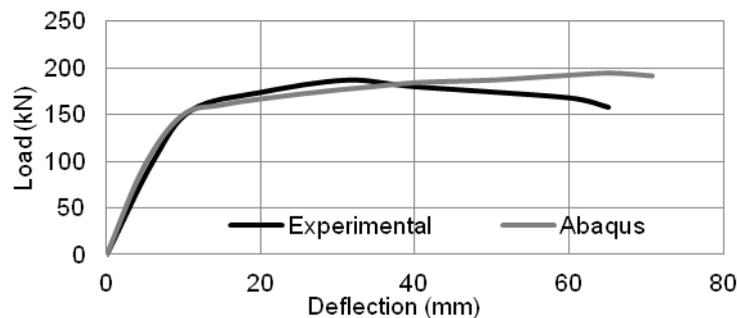


Figure 3a: Load-deflection curves for ABAQUS and Kotsovos et al ( $V_f = 0.4\%$ ) beam [3]

In addition, Figure 3b depicts ABAQUS results showing the beam deformations and the distribution of maximum principal stresses and strains. The principal stress vectors are also presented which provide a picture of the cracking pattern at failure.

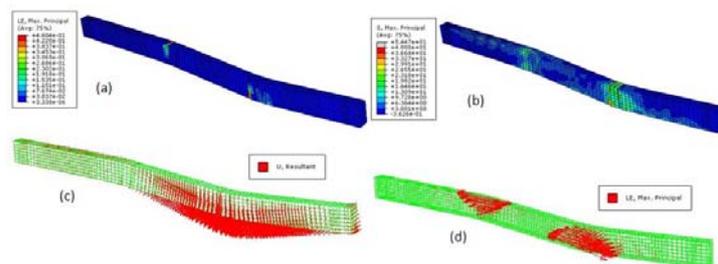


Figure 3b: ABAQUS modelling of Kotsovos et al [3] experiments showing maximum principal (a) strain and (b) stress contour distribution, (c) beam deformation and (d) principal stress vectors

### 3.2 Parametric studies

Once the calibration was completed, further parametric studies were carried out. First, the analysis was carried out for beam with VF=0%, 1%, 1.5%, 2% and 2.5%. Then, the spacing of the stirrups was increased by 50%, and analysed with 5 different fibres content ratios mentioned earlier (shear link spacing increase ratio (SI) is simply the ratio between the increase in spacing to the original spacing). Finally, further increases of spacing between stirrup was modelled (SI=100% from the original spacing), and analysed at different fibres content in volume. The results are discussed next.

#### 3.2.1 Shear link spacing increase SI = 0%

Figure 4 contains the numerical results obtained for SFRC beams with various volume fractions when the shear links spacing has not been increased (i.e. SI = 0%). The load-deflection curves show that the beam without fibres has less stiffness and maximum load-carrying capacity than those with fibres (with the increase in fibre content resulting in a gradual increase in both stiffness and strength). For fibre volumes to 1.5%, the increase in fibres has also led to enhancement of ductility. However, increasing the fibre volume further to 2% and 2.5% has actually resulted in reduced ductility. This suggests that a situation similar to the one experienced when main flexural reinforcement is increased beyond a certain threshold (i.e. over-reinforced) which leads to increase in strength but reduction in ductility. This is an interesting finding for the present case when the shear link has not been reduced, i.e. SI = 0%. This will be investigated further under increased shear link spacing.

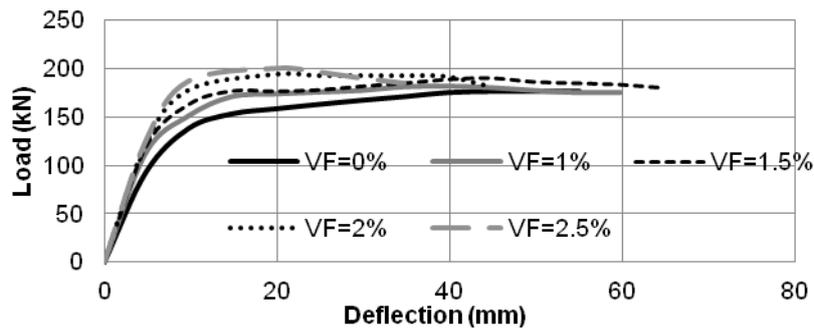


Figure 4: Load-deflection curves for monotonic load case (SI=0%)

These findings were confirmed using Table 1 below, which summarises the key results ( $P_{max}$  represents the maximum strength,  $P_u$  the ultimate (i.e. residual) strength,  $P_y$  the yield strength,  $\delta_y$  the yield deflection,  $\delta_u$  the ultimate deflection and  $\mu$  the ductility). The results of Table 1 also show that the residual strength is higher than ~92% of the peak strength in all cases, which indicates that the post-peak softening is not significant.

Table 1 : Results for SFRC beams with SI=0% (\* this ratio represents the change in maximum strength, † this ratio represents the change in residual strength)

Vf (%)	$P_{max}$ (kN)	$P_{max}/P_{max0}$ *	$P_u$ (kN)	$P_u/P_{max}$ †	$\delta_u$ (mm)	$\delta_y$ (mm)	$\mu = \delta_u/\delta_y$
0	176.99	1.0	176.99	1.0	54.97	9	6.11
1	181.45	1.03	174.98	0.96	59.73	9.1	6.56
1.5	190.66	1.08	180.53	0.95	64.48	9.5	6.79
2	194.15	1.10	181.49	0.93	44.75	9.69	4.62
2.5	200.3	1.13	185.15	0.92	34.71	9.69	3.58

### 3.2.2 Shear link spacing increase SI = 50%

The results for this case are presented in Figure 5 and Table 2 below.

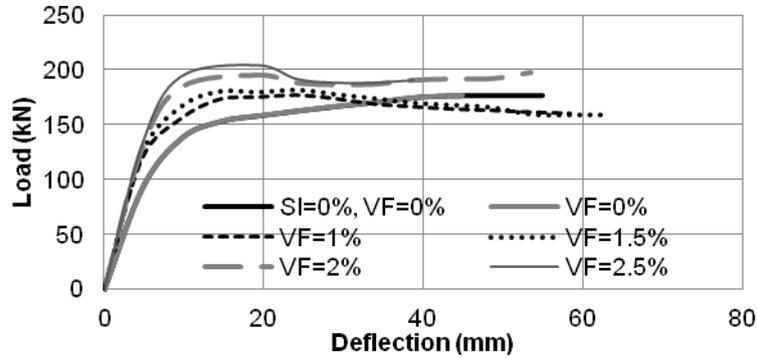


Figure 5: Load-deflection curves for monotonic load case (SI=50%)

The trend of the results is similar to the case of SI = 0%; however although ductility decreases at higher fibre contents, the decrease is less than in the case of SI = 0% (i.e. no spacing increase).

Table 2: Results for SFRC beams with SI=50%

Vf (%)	Pmax (kN)	Pmax /Pmaxo*	Pu (kN)	Pu/Pmax†	$\delta u$ (mm)	$\delta y$ (mm)	$\mu = \delta u / \delta y$
0	176.75	1.0	176.75	1.0	44.86	8.8	5.10
1	177.02	1.0	160.38	0.91	58.45	8.8	6.64
1.5	182	1.03	159.01	0.87	63.3	9.1	6.96
2	197.73	1.12	197.73	1.0	53.52	9.6	5.58
2.5	204.33	1.16	190.72	0.93	38.8	9.6	4.04

### 3.2.3 Shear link spacing increase SI = 100%

The results for this case are presented in Figure 6 and Table 3 below.

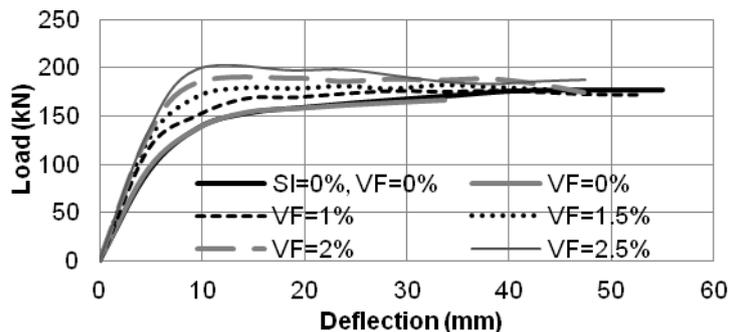


Figure 6: Load-deflection curves for monotonic load case (SI=100%)

Due to the significant increase in spacing of shear links (i.e. doubled), the shear strength has reduced when no fibres are provided. Subsequently, the addition of fibres has led to enhanced strength and ductility (the latter actually has high values now even at high fibre dosages). Although the

ductility enhancement did not increase beyond the level achieved at  $V_f = 1.5\%$  as observed in the previous two SI cases, however it did not reduce significantly by adding more fibres. This suggests that the fibres become more efficient in providing ductility in situations where there is a deficit of shear strength (e.g. in the current case SI has been increased by 100%). This is an interesting finding which indicates that in situations where providing shear links can lead to congestion, the links can be reduced and fibres can be used to compensate for loss of strength and ductility.

Table 3: Results for SFRC beams with SI=100%

$V_f$ (%)	$P_{max}$ (kN)	$P_{max} / P_{max0}^*$	$P_u$ (kN)	$P_u / P_{max} \dagger$	$\delta_u$ (mm)	$\delta_y$ (mm)	$\mu = \delta_u / \delta_y$
0	166.99	1.0	166.99	1.0	33.7	8.8	3.83
1	175.98	1.05	171.66	0.98	52.9	8.8	6.01
1.5	182.19	1.09	176.71	0.97	47.32	8.9	5.32
2	188.87	1.13	174.07	0.92	47.4	9.47	5.01
2.5	197.68	1.18	186.98	0.95	47.4	9.47	5.01

#### 4 CYCLIC-LOAD CASE

The same cases studies of SI = 0%, SI = 50%, and SI = 100% with inclusion of fibre contents between  $V_f = 0\%$  and  $V_f = 2.5\%$ , then were examined under reversed-cyclic loading. The input data for the analysis are given in Figure 7 below. The axial force was applied first on the beam and was then kept constant throughout the analysis.

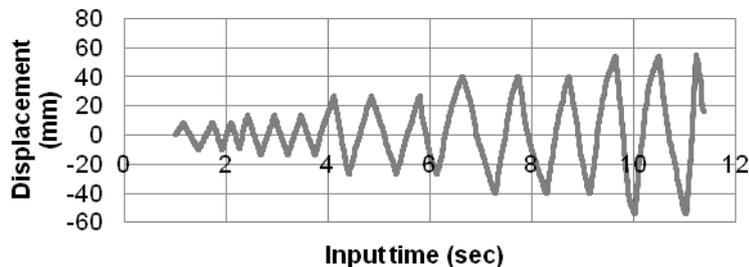


Figure 7: Input load time history (displacement based) used in ABAQUS for cyclic load case

##### 4.1 Calibration using experimental data

Initially, calibration work was carried out to compare the experimental results of Kotsovos et al (with  $V_f = 0.4\%$ ) [3] with ABAQUS predictions and the results are depicted in Figure 8 below. The results show good agreement between the experimental and numerical data.

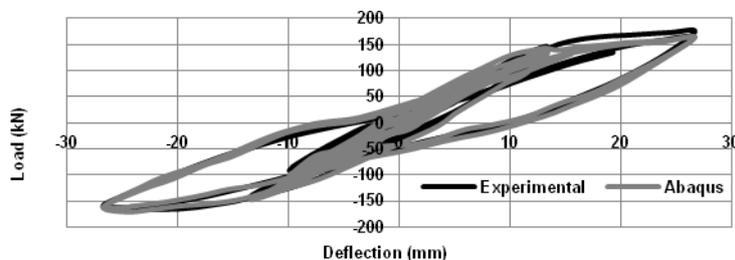


Figure 8: Cyclic load-deflection curves from ABAQUS and Kotsovos et al [3] beam

## 4.2 Parametric studies

### 4.2.1 Shear link spacing increase SI = 0%

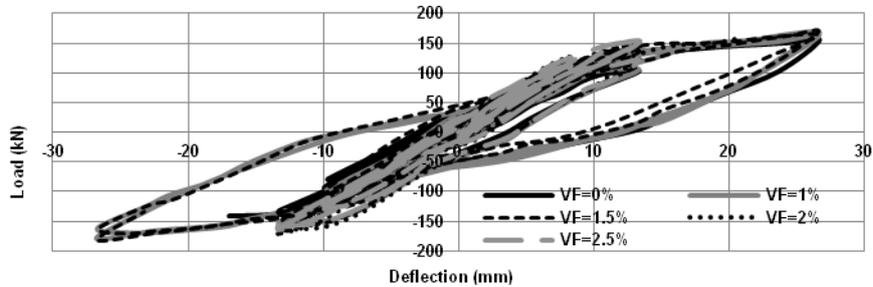


Figure 9: Load-deflection curves for cyclic load case (SI=0%)

Figure 9 and Table 4 show the results for this case. It can be seen that increasing the amount of fibres increased the load nominal yield of the beams. However, in term of ductility, there is an improvement only up to  $V_f = 1.5\%$ . After  $V_f = 1.5\%$ , the ductility of the structures decreased even more than the ductility of beam with no fibres. This suggests that the provision of fibres in addition to sufficient shear reinforcement can lead to brittleness as observed earlier in the monotonic-load case.

Table 4: Results for SFRC beams with (SI = 0%), NC represents the number of cycles before failure,  $\delta_y$  the yield deflection,  $\delta_f$  the deflection in the cycle before failure and  $\mu$  the ductility

Vf (%)	NC	$\delta_y$ (mm)	$\delta_f$ (mm)	$\mu = \delta_f / \delta_y$
0	6.68	7.99	26.63	3.33
1	8.58	7.99	26.6	3.33
1.5	7.78	7.99	26.6	3.33
2	6.21	7.99	20.48	2.56
2.5	5.5	7.99	13.38	1.67

### 4.2.2 Shear link spacing increase SI = 50%

The results are presented in Figure 10 and Table 5. When the spacing between stirrups was increased, addition of steel fibres increased the strength of the beam gradually. The same was observed with regard to ductility, however, the highest ductility was observed with  $V_f = 1.5\%$ . The number of cycles achieved before failure follows a similar trend.

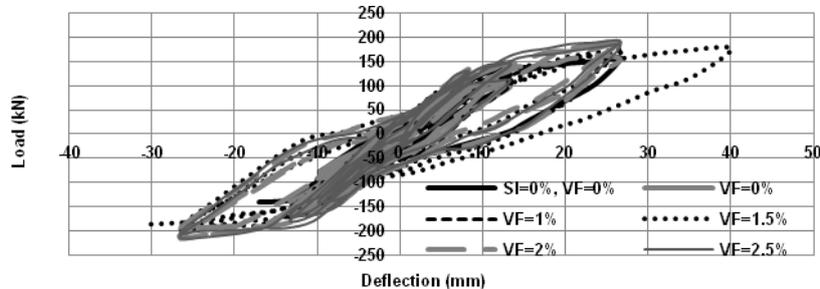


Figure 10: Load-deflection curves for cyclic load case (SI=50%)

Table 5: Results for SFRC beams with (SI = 50%)

Vf (%)	NC	$\delta y$ (mm)	$\delta f$ (mm)	$\mu = \delta f / \delta y$
0	4.2	7.99	7.04	0.88
1	6.25	7.99	22.25	2.78
1.5	9.71	7.99	37.68	4.72
2	8.98	7.99	26.6	3.33
2.5	8	7.99	26.6	3.33

#### 4.2.3 Shear link spacing increase SI = 100%

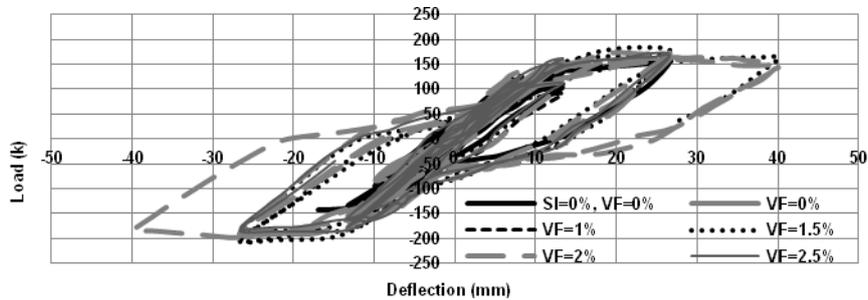


Figure 11: Load-deflection curve for cyclic load case (SI=100%)

The results are presented in Figure 11 and Table 6. Analysis results of SI=100% beams shows that inclusion of fibres increased the strength of the SFRC beams. Furthermore, the ductility also increased significantly with the maximum ductility was observed in Vf = 2%.

Table 6: Results for SFRC beams with (SI = 100%)

Vf (%)	NC	$\delta y$ (mm)	$\delta f$ (mm)	$\mu = \delta f / \delta y$
0	2.56	7.99	8.29	1.04
1	5	7.99	13.35	1.67
1.5	9.35	7.99	40.05	5.01
2	10.49	7.99	40.02	5.01
2.5	7.91	7.99	26.6	3.33

It can be concluded that the addition of fibres enhances ductility and the number of cycles (i.e. energy dissipation) and the optimum volume fraction seems to be 1.5%. The efficiency of the fibres increases when they are added to compensate for the reduction of shear links, however adding high amounts of fibres in addition to sufficient quantities of shear links can reduce ductility.

#### 4.3 Discussion of results

In order to make overall conclusions, figures encompassing key indicators of structural behaviour under cyclic loading and covering the practical range of fibres are discussed next. The basic idea is to depict the change in the number of cycles NC, deflection at failure  $\delta f$  and ductility ratio  $\mu$ . This is achieved by working out the ratio between the values of these parameters at given Vf and SI values to

their values at the basic case of  $V_f = 0\%$  and  $SI = 0\%$  (the symbols for the latter have a subscript "o" to denote this, e.g.  $NC_{/o}$ ). In this manner, the effect of adding fibres to compensate for increasing the links spacing can be quantified.

#### 4.3.1 Number of cycles (NC)

Figure 12a depicts the effect of adding fibres and increasing the links spacing on the number of cycles completed before failure. The results show that the increase in links spacing leads to a significant reduction in the number of cycles when no fibres are added (i.e. increased brittleness, which is expected). When the fibres are added, the number of cycles is enhanced. In fact, in most cases the original number of cycles with  $V_f = 0\%$  and  $SI = 0\%$  is restored and exceeded (i.e.  $NC/NC_o > 1.0$ ). However, there are some exceptions to this, namely when  $V_f = 1\%$  is used with  $SI > 40\%$  and when  $V_f = 2\sim 2.5\%$  with  $SI < 20\%$ . This suggests that too little fibres' amounts are insufficient beyond a certain spacing increase, while too high fibre amounts with small spacing increases lead to brittle behaviour. There seems to be an optimum fibre content in the region around 1.5%.

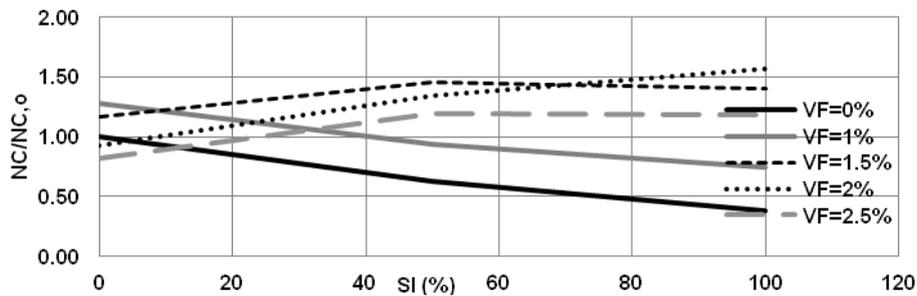


Figure 12a:  $NC/NC_o$  ratio – SI curves for cyclic load case

#### 4.3.2 Deflection at failure ( $\delta_f$ )

Figure 12b depicts the effect of adding fibres and increasing the links spacing on this parameter.

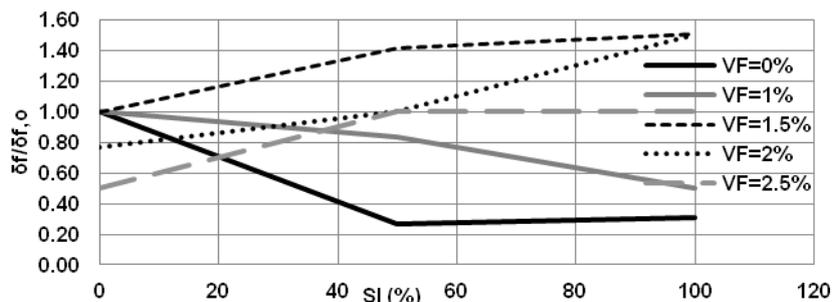


Figure 12b:  $\delta_f/\delta_{f,o}$  ratio – SI curves for cyclic load case

Again, the results show that the increase in links spacing leads to a significant reduction in the ultimate deflection (by about 70% when  $SI > 50\%$ ). Providing fibres with  $V_f = 1\%$  improves the performance, but does not restore the deflection to the level of the basic case (i.e. when  $V_f = 0\%$  and  $SI = 0\%$ ). Adding fibres with  $V_f = 1.5\%$  results in enhanced values of  $\delta_f$  at all SI values (i.e.  $\delta_f / \delta_{f,o}$  is always  $> 1.0$ ).  $V_f = 2\%$  provides better values of  $\delta_f$  only at  $SI > 50\%$ . Interestingly,  $V_f = 2.5\%$  provide a maximum of  $\delta_f / \delta_{f,o} = 1.0$  (i.e. no improvement on basic case). Both  $V_f = 2\%$  and  $2.5\%$  produce less  $\delta_f$  values (i.e. less ductile behaviour) when  $SI < 50\%$ , again pointing to brittleness due to over-strength when high amounts of fibres are added in addition to sufficient quantities of shear links.

#### 4.3.3 Ductility ( $\mu$ )

Figure 12c depicts the effect of adding fibres and increasing the links spacing on ductility. The trend is very similar to the one associated with the ultimate deflection  $\delta_f$ . Again  $V_f = 1.5\%$  seems to be the optimum volume fraction providing the highest ductility values, whilst  $V_f = 2\%$  and  $2.5\%$  provide reduced ductility at low SI values.

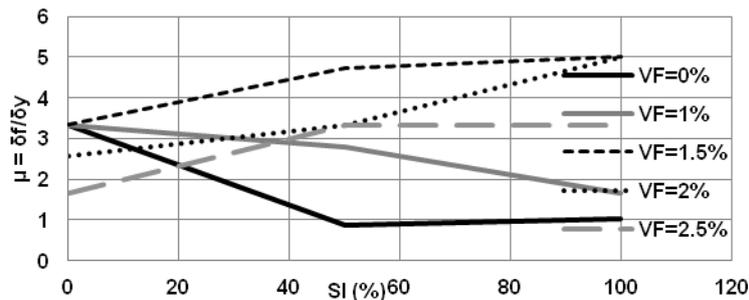


Figure 12c:  $\delta_f/\delta_y$  ratio – SI curve for for cyclic load case

#### 4.3.4 Cracking Pattern

An example representing an indication of cracking patterns at failure is presented in Figure 13 below for the cyclic load case with  $SI = 50\%$ . The principal stress vectors are used to reveal the cracking pattern. It is interesting to see that the increase in the fibre content provided has led to a reduction in the cracking zone suggesting that fibres are helping to control the propagation of cracks.

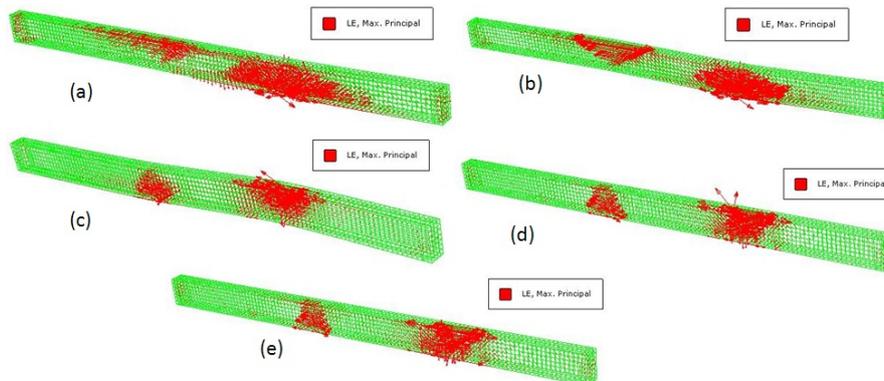


Figure 13: Principal stress vectors at failure for for cyclic load case ( $SI=50\%$ ) at (a)  $V_f=0\%$ , (b)  $V_f=1\%$ , (c)  $V_f=1.5\%$ , (d)  $V_f=2\%$  and (e)  $V_f=2.5\%$

## 5 CONCLUSIONS

SFRC beams under cyclic loading were investigated by means of NLFEA using ABAQUS software. A key issue assessed is whether the use of steel fibres can result in a significant reduction in conventional shear link reinforcement without compromising ductility and strength requirements. In this respect, the spacing between shear links was relaxed while steel fibres were added to see whether or not the loss of shear strength can be compensated for in this way. Parametric studies were subsequently carried out using the full practical range of steel fibre dosages and statically indeterminate SFRC beams were considered (under both monotonic and cyclic loadings) with increased spacing between shear links.

From these investigations, it can be concluded that the addition of fibres leads to an increase in both strength and ductility (and also an increase in the number of cycles achieved before failure). The increase in ductility is accompanied by a softening load-deflection response. However, the residual strength was found to be sufficiently high (i.e. >~85% of peak strength) in all cases studied, suggesting the softening is not significant. Nevertheless, the ductility seems to decrease when high amounts of fibres are provided (i.e.  $V_f = 2\sim 2.5\%$ ). This suggests that there is an optimum amount of fibres that can be added to enhance ductility and this was found to be around 1.5% in both the monotonic and cyclic loading cases studied. This is similar to the situation experienced when the beam main flexural reinforcement is increased beyond a certain threshold (i.e. over-reinforced) which leads to increase in strength but reduction in ductility. Thus, the addition of fibres is more efficient when the shear links spacing is reduced, however adding fibres in high amounts to beams with sufficient shear strength can actually lead to a less ductile response. Further investigations are needed on other beam arrangements to ascertain the optimum fibre dosages.

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