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To shear failure of steel and fibre-reinforced concrete circular hollow section composite column at elevated temperature

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Abstract

This study predicts the shear strength of steel fibre reinforced concrete (SFRC) members at elevated temperature using numerical modelling. The authors derived the stress-strain relation in the pure shear mode at ambient temperature based on a damage model calibrated at ambient and elevated temperatures. The model was validated on the special experimental arrangement for the pure shear mode of the SFRC in torsion. These results enables to determine the stress-strain diagram at elevated temperature. The shear strength of SFRC is compared with the compressive and tensile strength and used to observe reasons for experimentally observed failure model.

The work is a part of comprehensive project focused on development of design models for the steel and SFRC composite columns with circular hollow section (CHS) at elevated temperature. Research includes two levels accuracy/complexity, allowing simplified or advanced approach to design following the coming changes in European standard for composite member design in fire, EN1994-1-2:2021. Experimental studies of the project include mechanical material tests of heated fibre-concrete samples in tension and compression, thermal uniform and non-uniform tests of insulated fragments of CHS and tests of full scale SFRC CHS columns in steady-state and transient-state regimes. Developing advanced FEM simulation of global mechanical behaviour of SFRC CHS columns is a multi-levelled composite mechanical and thermo-model and provide numerous numerical experiments. Together with steel material model in fire, validated FEM model of mechanical behaviour of fibre-reinforce concrete at elevated temperature is performed. Validated simplified and advanced thermal model of SFRC in CHS at elevated temperature gives temperature fields and moisture distribution inside section which depends on direction, heat flux, sizes and gives possibility to model different fire cases of full-scale columns in bending, shear, and buckling at elevated temperature. Proposed analytical and simplified FEM mechanical model of column is taking into account degradation of mechanical properties, analytical models of transfer of heat inside the column section and provides simple solutions for designers.

Keywords: *Steel fibre reinforced concrete (SFRC); steel and concrete composite columns; circular hollow section; fire design; shear failure.*

1. Introduction

The wide use of concrete filled steel tubes (CFST) in high-rise buildings construction caused investigations of CFST members' behaviour which have been performed in the last three decades. Despite the presence of complexities in the studies of CFST structures, particularly their fire resistance, there is conventional set of questions in fire resistance assessment incorporated by their peculiar objects and characterized by principally similar ways of the solutions [1]. The first group is referring to the resolution of heat-and-mass transfer problem and its application to the sections of CFST members. As a rule, determination of temperature distribution over the section in short duration of heating is a first step to the assessment of fire resistance. The time-dependent pattern of temperature field can be obtained by using numerical approaches, finite difference method of solution of nonlinear differential equations of heat transfer with appropriate boundary conditions [2] or by utilizing powerful toolsets of finite element analysis [3]. Mandatory attributes of advanced software based on fine element (FE) approach such are the modules with ability to calculate the parameters of temperature field over the section. Also, due attention must be given to the software developed on the base of numerical methods. Comprehensive review of the state-of-the-art on the area of constitutive modelling of material (concrete and steel) at ambient and elevated temperatures was performed by Li & Purkiss [4]. Also, Youssef & Moftah [5] reviewed the developed constitutive law for concrete and reinforcement and proposed models, captured the changes that occur in the mechanical properties of concrete due to confinement effects and high temperatures. They also took into consideration transient creep, using a simplified but sufficiently accurate method. However, the above-mentioned reviews and investigations defining general trend of concrete behaviour at elevated temperatures did not consider general cases of volumetric stress strain for concrete and did not have application to the concrete with steel fibres. Investigations, which had been purposefully oriented on SFRC mechanical properties at the high temperatures, was not fully developed and constitutive law was for SFRC in the general case of volumetric stress state in the full temperature range has not been developed yet.

The third set of studies is oriented on large-scale model testing under fire conditions and development of analytical methods of fire resistance prediction. More than 300 large scale standard fire tests have been carried out globally on CFST columns of various types. The main contributors to the available test database for concrete-filled square hollow section are prepared by Kodur and Lie for the NRCC [6] and Kordina for the CIDECT [7]. Current practice is to use higher strengths materials [8]. Since 1954 more than 150 CFST columns were tested in fire and less than 5% had SFRC infill.

Numerical investigations of the structural members' fire resistance with FE approach - the forth direction of studies – have recently gained in importance. Certain boom of the works connected with rapid development of appropriate software is observed in the last decade. Representatives of research schools from China [9] performed series of CFST resistance simulation including condition of fire. Ren with colleagues showed importance of investigation of bending stiffness of composite CFST column [10]. Experimental studies and design solution within bending resistance of CFST members was summarized by Zhao et al [11]. Albero, Romero and Espinos' latest years researches was summarized in a proposal of a new method in EN1994-1-2 for the fire design of concrete filled steel tubular columns [12]. This research was focused on investigating behaviour of CFST filled with plain and bar-reinforced concrete.

Presented work is focused on mechanical behaviour and design models of CHS composite columns filled with steel fibre-concrete (SFRC) at elevated temperature [13]. Finalised research progressed in prediction models of material mechanical and thermal properties as well as global behaviour of columns in fire. Prepared models are available in two levels of accuracy/complexity, allowing simplified or advanced approach to design in the development of existing standards and include experimental studies. One of questions is the difference between the plane concrete behaviour and SFRC behaviour under elevated temperature. One answer, the study of the shear resistance et elevated temperature is presented here.

The use of steel-fibres as reinforcement in plain concrete not only enhances the tensile strength of the composite system but also reduces cracking under serviceability conditions [14]. Further, steel-fibres improve resistance to material deterioration as a result of fatigue, impact, shrinkage and thermal stresses see [15]. The improvements in material properties, which improve structural performance, have extended the use of fibre-reinforced concrete to applications in the area of fire. The addition of steel fibres to concrete is advantageous as the melting point of the steel fibres is relatively high in comparison to the other materials. It improves the mechanical properties of the concrete and its fire resistance in comparison to plain concrete, see [16] and [17]. A number of experimental investigations have been conducted up to date with the aim to observe the fire response of concrete composites. Particularly, the studies have focused on the effect of a type, shape and content of fibres on the mechanical properties of concrete composites, mostly compressive and tensile strength including elastic modulus. Different kinds of fibres including steel fibres, synthetic fibres and a mixture of steel fibres & polypropylene fibres have been studied [14]. Lau & Anson conducted a detailed review of previous investigations on the field of plane concrete (PC) and SFRC behaviour at elevated temperature, see [15]. They reported about series of test of SFRC mixtures at temperature range between 105°C and 1200°C. They studied compressive strength, flexural strength, elastic modulus and porosity of concrete reinforced with 1% steel fibre (SFRC) and changes of colour to the heated concrete have been investigated. The results showed that steel fibre remains beneficial to concrete which has been exposed to high temperatures up to 1200°C confirming that at 1%, steel fibre content has no deleterious effect on heated concrete. In fact, the inclusion of steel fibre in the concrete mix leads to an improvement in mechanical properties and a better resistance to heating effects. Balázs & Lublóy made series of tests with concrete mixtures containing polymer and steel fibre at temperature from 20°C to 800°C to investigate post-heating compressive strength of SFRC, see [17]. The test results show that the advantageous effects of polypropylene and steel fibres in concrete subjected to high temperatures are mainly observed for thin fibres and not for thick fibres. Strength reduction and surface cracking are detailed for the various tested fibre-reinforced concretes. Kim et al. studied the factors influencing the mechanical properties of steel-fibre-reinforced concrete exposed to high temperatures, see [18]. Test specimens reinforced with fibres of two types (twisted or hooked) and three series of fibre contents (volume fractions of 0.25%, 0.5%, or 1%) were tested after exposure to four different maximum temperatures (room temperature, 300°C, 500°C, and 700°C). Test results show that the residual compressive strength, tensile strength and rupture energy of the specimens decreased with their increased heating. After the SFRC was exposed to the high temperatures, the relative loss in tensile strength was higher than that in compressive strength, but the relative loss of rupture energy was comparatively lower. After exposure to high temperature, the behaviour of the samples was more sensitive to the volume fraction and aspect ratio of the fibre than to its type. As a result, authors proposed a model of prediction of the residual tensile strength of heated SFRC based on the test results. Also, the resent state of influence of elevated temperature to SFRC was clearly presented. Generally, the mechanical properties like compressive strength and tensile strength of fibre reinforced concrete at elevated temperatures have been studied sufficiently while the shear strength did not. There is a noticed gap of knowledge on the shear resistance of fibre reinforced concrete both at ambient and elevated temperature. In reality some applications of fibre reinforced concrete are frequently arranged to carry shear forces. There is a lack of realized experimental investigation on the performance of fibre reinforced concrete in pure shear mode without any flexural effects at elevated temperature.

In this paper a is investigated the pure shear resistance of fibre reinforced concrete at elevated temperature. A parametric study is done in order to fully explore the shear properties of fibre reinforced concrete.

2. Validation

Ráček et al. [19] investigated the pure shear resistance of fibre reinforced concrete at ambient temperature by creating a special new experimental arrangement. Pure shear was produced on the thin walls of the simply supported fibre-concrete by the application of torque. The objective of the experiment was to measure not only the ultimate strength but also the descending post-peak of the torque-twist diagram. This descending part of the diagram is very informative for composites with fibres. Experimental results bring new and important information essential for comprehensive understanding of fibre-concrete. These results enable to derive the stress–strain relation in the whole range of stress-strain diagram in the pure shear mode. Stress- strain diagram based on experimental results is presented in Fig. 1.

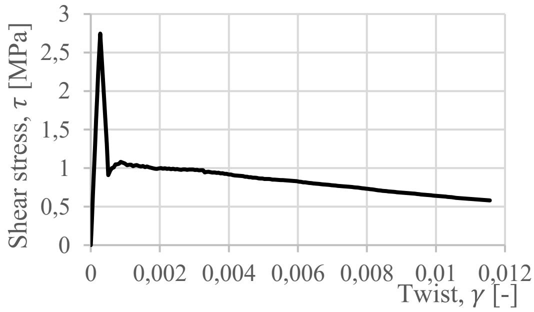

Fig. 1. Stress- strain diagram of SFRC at 20 °C

The software ATENA was used in the present study to model the pure shear model. This software package is mainly specialized and developed for the computation of concrete structures. The three dimensional model used for the pure shear properties of fibre reinforced concrete was validated against the experimental test which was conducted in Czech Technical University in Prague [13].

The properties of the fibre reinforced concrete which were used in the model were determined by an experimental test within the project. A hybrid fibres with a combination of steel and polypropylene ware used for the experiment and the same material in the numerical modelling [14]. The amount of fibres used in the concrete was 1.7% in weight. Experimental tests were performed on conventional bodies at normal temperatures and elevated temperatures of 200 ° C, 400 ° C and 600 ° C. On the basis of the acquired knowledge a material model was made, which is to serve for numerical simulations of 3 dimensional models in ATENA. The input material properties of SFRC which were used in ATENA software at different temperatures are given in [20].

Support and load conditions were applied to the FE models according to the test. Load was applied at the top of one of the cantilever arm, see Fig. 2. The supporting conditions on the model were also made in similar arrangement which recreate the test conditions. The master- slave fixed contact surface was used to connect the tube concrete and the steel cantilever.

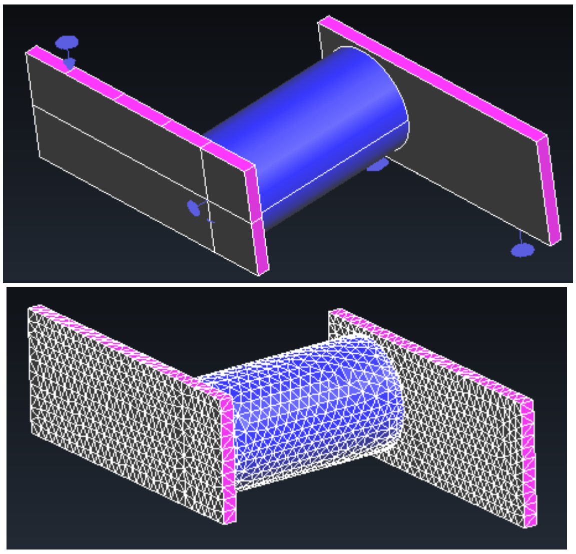

Fig. 2. Model, loading, support conditions and meshing of the model

The validation process was performed through the comparison of the failure mechanisms in between the numerical analysis and the experimental test. The orientation of the diagonal crack which was obtained both through the experiment and the numerical model is presented in Fig. 3. Fig. 4 shows the sensitivity of the quality of mesh size to the prediction of the failure mode.

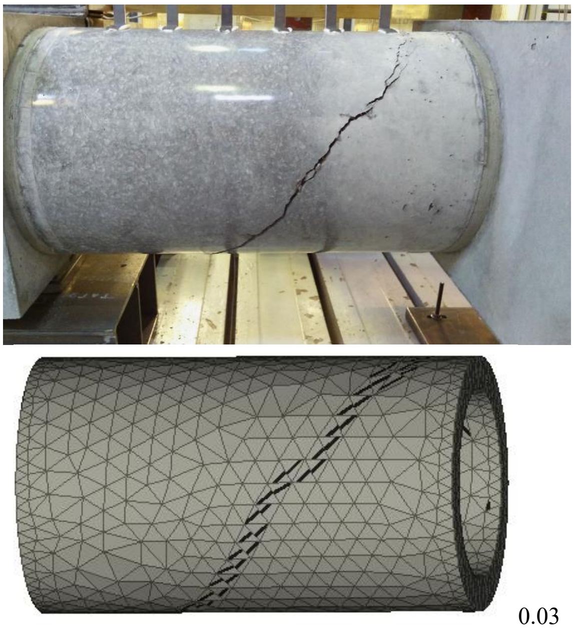

Fig. 3. Comparison of the experimental and numerical failure mode with 0.03 mesh

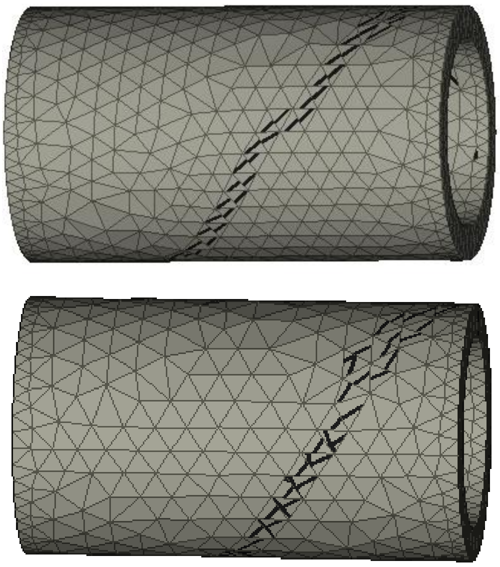

Fig. 4. Sensitivity of mesh to prediction of failure modes, 0.04 mesh, 0.05 mesh.

3. Sensitivity study

Sensitivity study is a desired element of the experimental work and an essential part of the numerical analysis. The cost and time needed to perform a number of experimental study in order to investigate the response behaviour of different parameters is very high, but these difficulties can be reduced with the help of numerical analysis significantly. The validated model can be used to investigate the structural behaviour by conducting a sensitivity study on different parameters.

As the main interest of this paper is the shear resistance at elevated temperature, a sensitivity study is done by choosing different temperatures of concrete. Material input characteristics of fibre reinforced concrete at elevated temperatures of 200°C, 400°C and 600°C were already studied. Therefore, these temperatures were used to study the pure shear characteristics of fibre reinforced concrete.

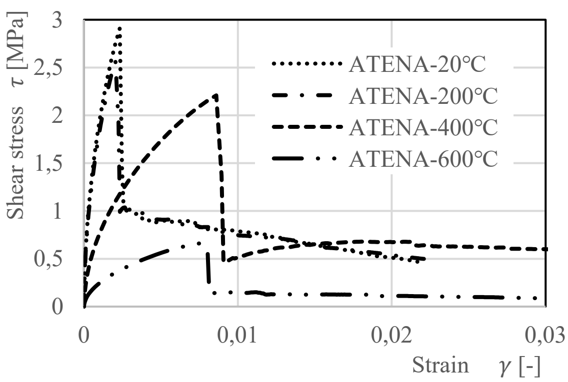

Fig. 5. T Shear stress - strain diagram for SFRC at elevated temperatures

*Table 1.*Tthe ultimate compressive, tensile and shear strength of SFRC and its % decrease at elevated temperatures.

Temp. (°C)	**Compr.** [MPa]	**Tensile** [MPa]	**Shear** [MPa]
20	62	4.4	2.91
200	57	3.8	2.57
400	52	3.6	2.21
600	29	1.4	0.66
	Decres. %	**Decres.** %	**Decres.** %
20	0.0	0.0	0.0
200	-8.1	-13.6	-11.8
400	-16.1	-18.2	-24.1
600	-53.2	-68.2	-77.3

To investigate the mechanical properties of fibre reinforced concrete at elevated temperature in case of pure shear, it was necessary to rely on the numerical model which was verified against the experimental results at ambient temperature, because it was not possible to find experiments conducted at elevated temperature for the pure shear resistance of fibre reinforced concrete. Using the numerical model, shear characteristics of fibre reinforced concrete at temperatures of 200°C, 400°C and 600°C was studied. In order to compare the results of the shear strength at elevated temperature, the percentage decrease of the shear strength was checked against the experimentally obtained percentage decrease of compressive and tensile strength of the fibre reinforced concrete at each given temperatures of 200°C, 400°C and 600°C. The results are provided in Tab. 1. and in Fig. 5. Looking on the results, the percentage decrease of the shear strengths lies close to the range of the percentage decrease of compressive and tensile decrease. Therefore, it is concluded that the results of shear strength from the numerical experiment was genuine.

4. Failure modes

Based on validated model for pure shear behaviour the failure of the SFRC et elevated temperatures were studied and validated on experiments for failure of cubes, see Fig. 6 from [20].

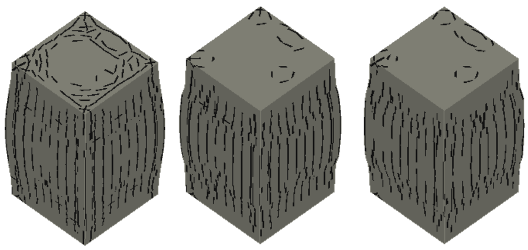

Fig. 6. Uniaxial compression failures of SFRC prisms 150 x 150 x 300 mm at 20 °C, 400 °C and 600 °C

By observing the failure mechanisms of all the conditions of the column, two failure modes were identified. When the axial load is applied without any eccentricity at any temperature, the FRC column fails in compression by crushing. However for the loads applied with the eccentricity of 10 mm and 30 mm, the failure is a combination of flexural and compression, see Fig. 7. Because of the end conditions of the column, i.e. pinned at the top and fixed at the bottom, the sensitive area of the column is close to the upper end with more bending and cracking noticed over there. The pattern of the cracks for the columns with eccentricities has shown that there is a development of a diagonal shear cracks. Due to the eccentricity of the load a flexural moment will be produced and in turn this moment will create a shear force on the column. Thus the column is subjected mainly to compression and bending but also to the shear force. As noticed on the properties of a cube tensile properties of the SFRC decreases significantly with temperature, and these will result in the formation of shear cracks.

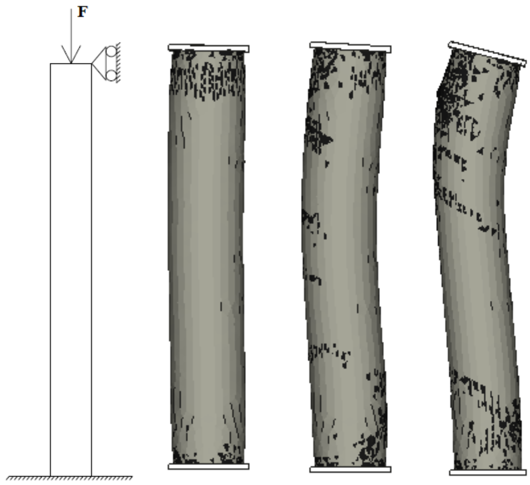

Fig. 7. Failure modes of FRC column at 400 °C with eccentricities 0 mm, 10 mm and 30 mm

5. Summary and application

The relative loss of tensile strength is more than the relative loss of compressive strength for the fibre reinforced concrete from Tab. 1. On the other hand it was found that the relative loss of shear strength of the fibre reinforced concrete was more than the relative loss of tensile strength for temperatures above 400 °C.

From the numerical results it can be generalized that the shear strength and tensile strength of fibre reinforced concrete are closely related to each other and the shear strength can be predicted from the tensile strength. But always the ultimate shear strength of fibre reinforced concrete is smaller than the ultimate tensile strength of fibre reinforced concrete. At temperatures between 0 °C and 200 °C the ultimate shear strength is about 68% of the ultimate tensile strength, at 400 °C it is about 61% and it is approximately 47% at 600 °C

Generally, from this numerical modelling it can be concluded that at elevated temperature fibre reinforced concrete loses more of its shear resistance compared to the tensile and compressive strength. Therefore, it is recommended that in the design of fibre reinforced concrete at elevated temperature to consider the shear resistance in addition to the other mechanical properties of concrete like compressive and tensile strengths.

The failure modes of SFRC cube and column is greatly affected by the boundary condition and loading environment. It well described the space stresses under the thick load plate and combination of failure in buckling and cracking of top of the column, in plane of main stress inclined due to geometrical and structural imperfections of inhomogeneous material.

This research is focus to preparation of European approach for design solutions of SFRC CHS columns in fire. Presented experimental studies on SFRC composite columns are covering disproportion in available fire tests results, compare to plain and bar-reinforced concrete infilling and used for validation model of transfer of heat inside hollow section and global behaviour mechanical model. Results of FEM modelling are used to develop the analytical solutions to design SFRC CHS columns in fire.

6. Acknowledgement

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