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Residual Stress – Strain Relations Inversely Derived from Experimental Moment - Curvature Response of RC Beams with Fibres: Comparison to RILEM Recommendations

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Abstract. This study aims to investigate adequacy of the RILEM residual stress modelling approach. For this, the residual stress strain relations composed using the tests results of standard notched beam are compared to the stress - strain diagrams inversely obtained from the experimental moment-curvature response of RC beams reinforced with steel fibers. For this purpose, an experimental study of 8 full-scale SFRC beams with longitudinal reinforcement bars including the tests of standard notched beams was carried out. The varying parameters were volume levels of fibres and reinforcement ratio. To produce accurate moment – curvature diagrams, the beams were tested in four-point bending with measured strains at four levels throughout the constant bending zone. The predicted curvatures of SFRC beams following the RILEM recommendations were compared to the tests. Similarly, the residual stress - strain relations inversely derived from the structural tests were compared to the RILEM model.

INTRODUCTION

The shortcomings of concrete as a material are well known and well established throughout the years. It severely lacks in tensile strength by itself, hence in practice it is almost always used with additional longitudinal reinforcement bars. This allows the material to retain some capacity even when cracking occurs, as the stresses are transferred through the bond-action from the concrete to the reinforcement and vice-versa. However, there are alternative ways to improve the cracking resistance of concrete and its toughness. One of them is by the addition of steel fibres into the concrete composition. Such a composite material is known as steel-fibre reinforced concrete (SFRC). The inclusion of fibres can significantly modify the post-cracking behaviour of the composite material, but it has little effect on the pre-cracking tensile capacity and has marginal impact on the cracking initiation [1].

In practice, most structural elements that are made of SFRC also contain longitudinal reinforcement bars. The present study considers beams reinforced with steel fibres and longitudinal tension and compression bars. Carrying out serviceability analysis of such members is not a trivial task. In the post-cracking stages, the tension zone can be expressed through the tension stiffening stresses and the residual stresses that appear due to the steel fibres spanning the cracks. Tension stiffening stresses depend on the bond strength between the bars and the concrete.

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This study aims to investigate adequacy of the RILEM TC 162-TDF 2002 [2] residual stress modelling approach. Residual stress - strain relations composed using the test results of standard notched beams are compared to the stress - strain diagrams inversely obtained from the experimental moment-curvature response of RC beams reinforced with steel fibers. For this purpose, an experimental study of 8 full-scale SFRC beams with longitudinal reinforcement bars including the tests of standard notched beams is carried out. The varying parameters are volume levels of fibres and reinforcement ratio. The predicted curvatures of SFRC beams following the RILEM recommendations are compared to the tests. Similarly, the residual stress - strain relations inversely derived from the structural tests are compared to the RILEM model.

EXPERIMENTAL INVESTIGATION

Full scale concrete beams reinforced with steel fibre and longitudinal bars were tested in a flexural loading experiment. In addition, small samples were tested to determine the material properties such as the compressive and tensile strengths of the concrete and reinforcement steel. The obtained experimental results were used to calculate the simplified tensile stress-strain responses by applying an inverse analysis technique.

In accordance with the EN14651 [3] recommendations, the post-cracking behaviour or SFRC was determined experimentally from scaled down standardized beam tests. In total, 26 SFRC beams of 150×150×600 mm dimensions were employed for the standardized tests.

The methods recommended by RILEM [4-6] and Model Code 2010 [7] were employed to determine the mean values of the post-peak parameters. Residual stresses were obtained for all beam series. The values obtained by Model Code 2010 and RILEM are relatively similar and in some cases identical. In general, results confirm the softening response of the SFRC beams.

RESULTS FROM THE FULL-SCALE BEAM EXPERIMENTS

In total, 11 full-scale reinforced concrete beams, reinforced with various quantities of steel fibres and tensile steel bar combinations were tested to failure. The tests were carried out under short-term loading condition with a four-point bending layout. These tests enable the investigation of combined action of both the tensile bar reinforcement and the steel fibres.

The nominal lengths of the 11 full-scale beams were either 3100 or 3280 mm. To ensure comparability, the span was chosen as 3000 mm for all beams. The beam cross-sections were close to full square, with the dimension of the height at 300 mm and the width at 280 mm. The longitudinal tensile steel bars of these full-scale beams were chosen as to provide the following reinforcement ratios: ρ = 1.0, 0.6 and 0.3% for series 1, 2 and 3 beams, respectively. Steel fibre volumes used in these beams ranged from 23.5 kg/m3 to 118 kg/m^3, which is equates to approximately 0.3, 0.5, 0.6, 1.0 and 1.5% of the total specimen volume. The steel fibres were all used with hooked ends. For comparison purposes, reference beams were cast without any fibres for each of the beam series.

The deflections were measured using linear variable displacement transducers (LVDT). They were installed on the bottom surface of the SFRC beams. ALMEMO T50 was used to record the displacements with an accuracy of ± 0.15%. Signal processing device ALMEMO 25 90-9 was utilized to record the LVDT and dynamometer readings every second directly to a computer. In order to determine the exact cracking moment M_{cr} of each tested beam, LVDTs, mechanical micrometres and visual examination were used of the first crack. Since the tests were carried out until failure, ultimate moment Mu values were also obtained.

A comparison of the moment-curvature diagrams of the Series 1, 2 and 3 beams were performed. While the fibre reinforced beam results are relatively close to each other, the reference beam results, with no steel fibres, were visibly different. The variation in the volume of steel fibres, from 0.5% to 1.0% for the Series 1 and 2 beams and from 0.3% to 0.6% for Series 3 beams did not have a pronounced influence on the flexural stiffness.

DEFORMATION ANALYSIS OF FLEXURAL MEMBERS

The predicted moment-curvature charts, with post cracking behaviour evaluated using RILEM methodology, were performed. Overall, a satisfactory agreement between the experimental test results and the predicted ones can be observed. For most of the test beams, the predicted response was too stiff compared to the test results. The difference was more pronounced for the members having smaller reinforcement ratio and higher amounts of fibres. The discrepancy between the predicted and experimental moment-curvature lines increased with the loading level.

The basic idea of the inverse calculation concept, is defining a constitutive relationship based on the experimental curvature response of the structure. Kaklauskas and Ghaboussi proposed [8] a method for determining average stress-average strain relationships for concrete in tension using experimental moment-curvature diagrams of flexural RC members. This approach was applied for deriving residual stress – strain relations for SFRC based on the current tests of RC beams reinforced with fibers.

After completing the inverse analysis, residual stress charts were obtained for the tested SFRC beams (see Figs 1, 2 and 3). For comparison, the RILEM model is overlayed onto these charts.

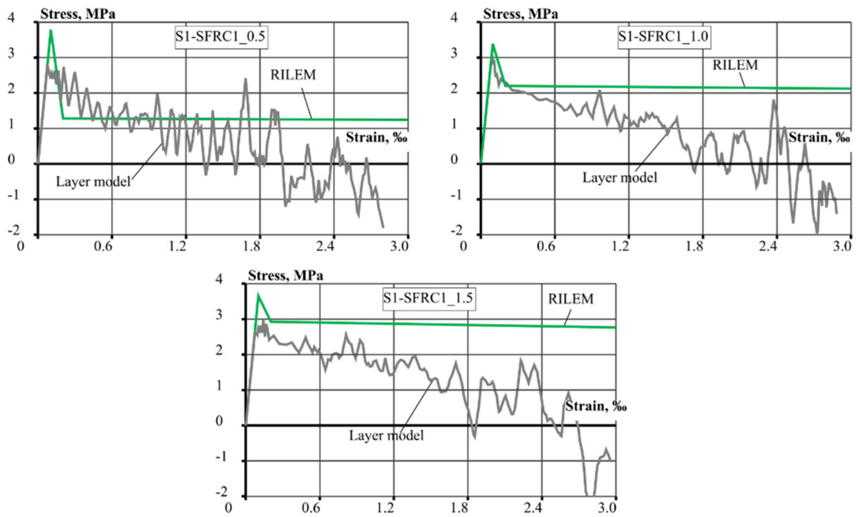

FIGURE 1. Comparison of residual stresses of the beam series S1-SFRC1

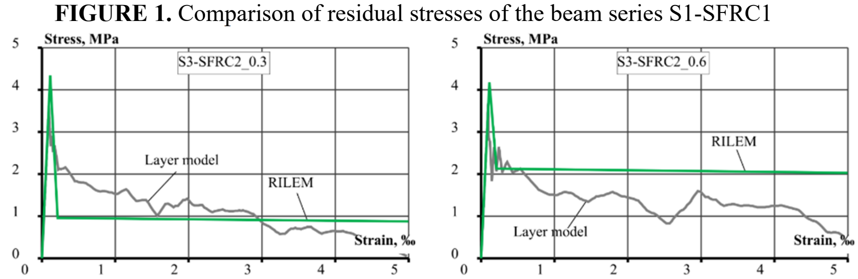

FIGURE 2. Comparison of residual stresses of the beam series S2-SFRC1

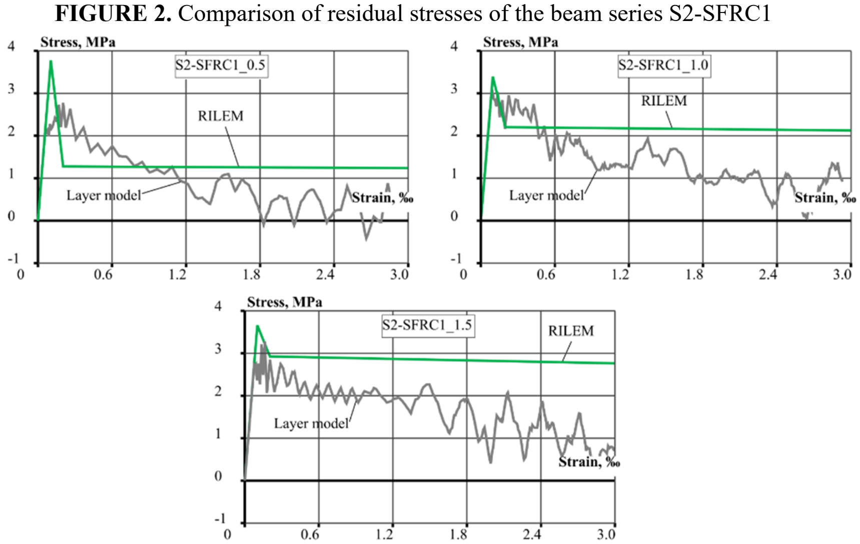

FIGURE 3. Comparison of residual stresses of the beam series S3-SFRC2

Initially, when the strain levels are very low, the maximum estimated residual stresses are relatively close to the RILEM model. With further increase of strain values, the predicted residual stresses drop begin a steady decline and eventually drop below the RILEM model values. Regardless of the steel fibre volume present in the full-scale SFRC beams, residual stresses in all cases display the same pattern.

CONCLUDING REMARK

- The results of the experimental 3 point bending tests of standardized SFRC samples and 4 point bending tests of full-scale beams reinforced with fibres and bars reveal substantial differences in the cracking behaviour. While the behaviour of standard beams is governed by the progression of a single crack that can be modelled by the tension softening phenomenon, the beams reinforced with bars and fibres have multiple cracks to be simulated by the combined action of tension softening and tension stiffening effects. Beams with higher densities of steel fibres and larger amounts of longitudinal reinforcement display more extensive cracking.
- The residual stress – strain relations of SFRC in tension inversely calculated from the experimental moment - curvature diagrams of structural beams can be approximated by a three-linear diagrams consisting of three parts: ascending linear branch with the maximum stress being equal to the tensile strength of concrete, a sudden stress drop, and a linear descending branch. Qualitatively, the stress – strain diagram in shape is similar to the relation assumed by RILEM TC 162-TDF recommendations based on the tests of standard notched beams.
- In quantitative terms, these two relations have both similarities and differences. While maximum residual stress at low strain values were observed to be relatively similar, the descending branch inversely calculated for the structural member with increasing strain degraded much faster than the one predicted by RILEM TC 162-TDF recommendations.
- The implemented RILEM TC 162-TDF model for the prediction of the moment-curvature response of the full-scale SFRC beams reveals that it tends to underestimate the curvature when compared to the actual experimental results. This observation is valid for all cases of tested fibre volumes, ranging from 0.3% to 1.5%. The discrepancy between the prediction and the experimental result only increases further with the increase of the applied load and the fibre amount.

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