Application of SFRC to encased steel-concrete composite beams: experimental study

Aplicación de hormigón reforzado con fibra de acero a vigas mixtas de acero y hormigón revestidas: estudio experimental

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RESUMEN

El artículo describe ensayos de vigas estructurales a escala real que investigan el uso de hormigón reforzado con fibra de acero en estructuras mixtas de acero y hormigón. En particular, se estudia la tipología de puentes con vigas empotradas en losa de hormigón. Los experimentos demuestran que les fibras de acero permiten alcanzar una importante capacidad de rotación de la sección transversal gracias a la superior ductilidad del hormigón. Esto permite optimizar el rendimiento del componente de la viga de acero, mejorando el comportamiento estructural tanto en el estado límite último (ELU) como en el estado límite de servicio (ELS).

ABSTRACT

The paper describes full-scale structural beam tests investigating the use of steel fiber reinforced concrete (SFRC) for steel-concrete composite structures. In particular the bridge typology of filler beam decks is object of this study. The experiments shows that SFRC permits to reach an important cross-section rotation capacity thanks to the superior concrete ductility. This permits to exploit the steel component at its best, improving the structural behavior both at Ultimate Limi State (ULS) as well as at Serviceability Limit State (SLS).

PALABRAS CLAVE: Hormigón reforzado con fibras de acero, sección mixta revestida
KEYWORDS: steel-fibre reinforced concrete, encased composite section, filler beam decks

1. Introduction

Concrete is the most used construction material worldwide, and the idea to improve its behavior by adding diffuse fibre reinforcement in the matrix goes back to its beginning but is finding its way in engineering practice only recently. Fibre reinforcement for concrete matrix may be realized out of a variety of materials; amongst them steel fibres remain the preferred solution for structural applications thanks to their reliable strength properties (for such application the yield strength is commonly above 1200 MPa) achieved by an industrial process. This permits to guarantee a moderate material cost compared to other solutions with similar strengths, widespread availability and reliable supply chain. Moving out of their main field of applications such as industrial floors or tunnel linings, over the past decade the trend has showed an increased use of steel-fibre reinforced concrete (SFRC) in other structural applications. Beside playing a significant role at Ultimate Limit State (ULS) as well as at Serviceability Limit State

(SLS), they may bring also benefits in other specific situations (e.g. reduced concrete spalling in case of fire exposure). The structural behaviour of fibre reinforced concrete has been intensively researched over the last decades [1] and the knowledge is now mature for being transferred into concrete design codes such as the forthcoming Eurocode 2 [2]. Beside a simplified model for the tensile resistance, it is worth mentioning that a new analytical model for SFRC in compression has been introduced based on the works by Ruiz, De la Rosa, Poveda et al. [3],[4],[5],[6]. This model permits to consider the increased ductility in compression conferred by the steel fibres. Structural concrete is also used in combination with steel for composite structures according to Eurocode 4 [7]: using SFRC permits indeed to enhance a specific spectrum of common Structural typologies as outlined by Zanon et al. [9]. Detailed experimental and numerical research studies were already performed concerning the application of SFRC for composite columns with encased steel sections; to mention in particular the work by Venkatesh, Lai, Liew et al. [10],[11],[12].

The research work presented in this paper concerns the structural behavior of steel profiles encased in SFRC as filler beam decks according Eurocode 4 [7], a common solution used for overpasses in railway and roadway bridge construction. In this typology the full cross-section is embedded in the concrete slab, whereas only the bottom flange is outstanding and supporting the lost formwork.

2. Full scale bending tests

2.1 Test configuration

The investigated beam is a specimen with constant cross-section formed by one structural steel profile, longitudinal straight rebars and transversal rebars formed by open stirrups in the top part overlapping with one transversal bar through the web to close the loop (Fig. 1). The concrete matrix is foreseen with steel reinforcement fibres – this latter addition being the innovative component in the system. The cross-section is compliant with the geometrical requirements of Eurocode 4 [7] for filler beam decks, having the width corresponding to the centre distance of two longitudinal beams. A simple hooked end out of high-resistant drawn wire obtained by an electric arc furnace route ensuring a tensile strength of 2150 MPa was chosen [8]. The diameter is 0.75, length 35 mm and the aspect ratio is therefore 47; being relatively small and light it permits to have a very diffuse and local action in the whole matrix. To give an idea, for a dosage ratio of 50 kg/m^3 there are averagely 410 fibres in a cube of 10 cm edge. The specimen is tested as simply supported beams with a span of 4.2 m, with the load applied in the centre as a three-point bending configuration (see Fig. 1). The beams are supported on elastomeric bearings which allows free rotation as well as no constraint in axial direction. A total of 6 monotonic beam tests have been performed, 3 under sagging bending moment and 3 under hogging bending moment, whereas it has been sufficient to turn the specimen of 180 degrees along its axis without major changes in the test configurations (Fig. 1).

2.2 Specimen production

Steel beams, steel reinforcements and steel fibres have been sourced in Luxembourg. They have been purchased specifying a supply out of the same production batch to allow for minimal properties variation. They have been delivered and assembled in a concrete prefabrication plant in Herencia, Spain, close to the testing laboratory. Here the concreting of all the specimens was scheduled over one intense month where 16 concrete batches were casted to obtain 16 real scale specimens and over two hundreds of small coupons. The specimens were then stored inside before being tested.

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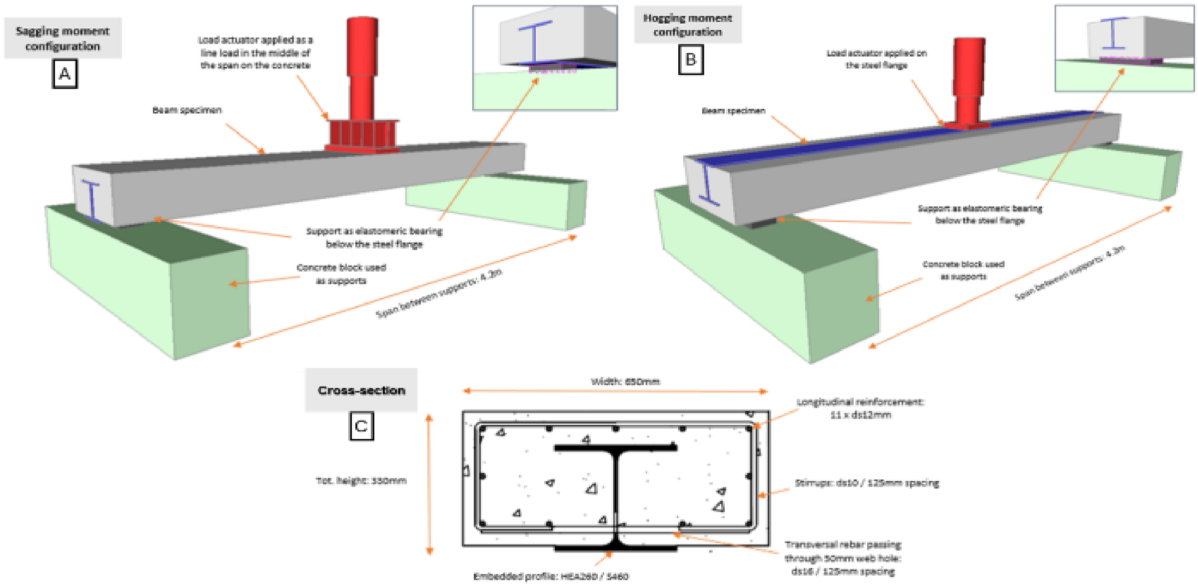

Fig. 1. Cross-section of the test specimens. Test setup for sagging (A) and hogging (B) bending moment

The reinforcement cages were kept in place by hanging them on external upper supports above the molds; few spacers were used. Metallic molds were created specifically for this project. The concreting happened with a normal concreting batches (see Fig. 2) having the filling achieved in 3 different passes to reach the total height of the beam. After concreting the specimens were placed on the shaking table of the prefabrication plant; they were vibrated for about 10 seconds. There have not been specific measures concerning the fibre orientation in the real scale specimen; nevertheless in all the test specimen (including some opening of the specimen after the tests) no anomalies or undesired effects in term of preferred fiber orientation, fiber segregation or- concentration.

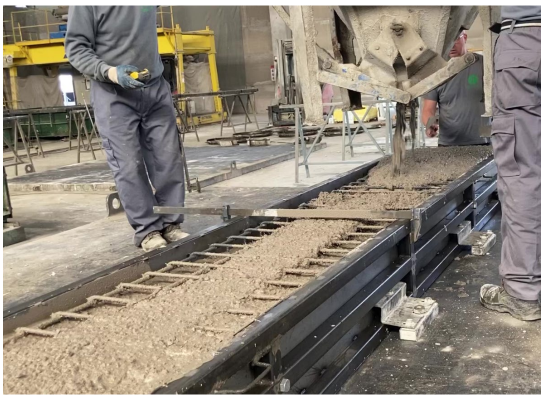

Fig. 2. View of the specimen during concreting

2.3 Characterization material properties

Steel profiles and rebars were characterized via standard tensile tests; results are given in Table 1. Concerning the choice of the steel-fibre reinforced mix, a preliminary experimental campaign was conducted where 4 concrete mixes were designed based on a methodology developed by UCLM [13]. The wish was to have concrete with good mechanical properties but capable of being casted on site with costs and efforts comparable to the plain concrete traditionally used for these applications. Batches were produced and tested to measure rheological and mechanical properties. This phase is described in detail by De La Rosa et al. [13]; the chosen mix foresees a conventional dosage ratio of cement 380 kg/m^3, water to cement ratio (w/c) as 0.48, an adequate choice of aggregate nature and distribution, steel fibre volumic ratio of 0.6%. The concrete consistency class is S4 according to [14].

This concrete mix was used to cast the full scale specimens. The compression properties were characterized by means of cylinder specimens and cubic specimens of 150mm and 100mm edge. The results confirmed the predictive stress-strain law proposed by Ruiz et al. [8] for SFRC in compression (see Fig. 3), whereas the presence of fibres guarantees an inherent higher ductility due to achieved confinement. The concrete was classified C45/55 concerning compression properties.

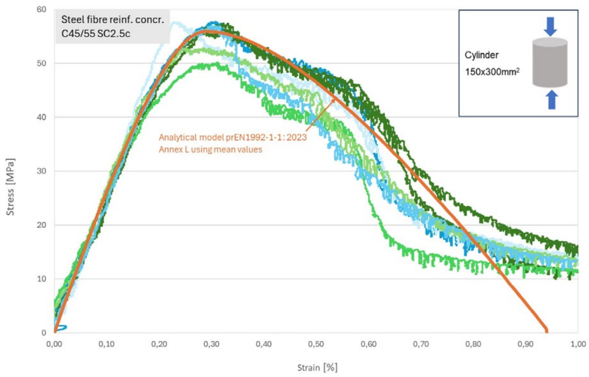

Fig. 3. Cylinder compression test on the SFRC mix

The tensile properties were characterized via three-point bending tests of notched specimens. The results show scatter with a notable difference between the average values and the characteristic ones. The SFRC has been classified as a 2.5c according to the new standard [2] results are in Table 2.

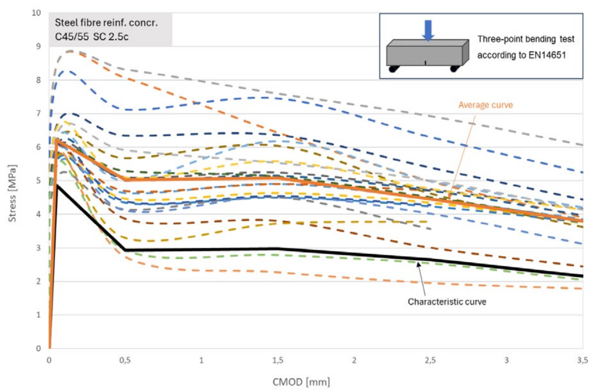

Fig. 4. Three-point bending test on the SFRC mix

Table 1. Steel material properties

Component	Class	Rp0.2 [MPa]	Rm [MPa]
Profile	S460M	480	612
Rebars	B500B	624	720
Steel fibres	HE++75/35		2150*

** Technical sheet nominal value*

Table 2. Steel fibre reinforced concrete properties

Class	f_{cm} [MPa]	E_{cm} [MPa]	$f_{R,1k}$ [MPa]	$f_{R,3k}$ [MPa]
C45/55 2.5c	55.9	33 302	2.93	2.65
St. deviation	2.96	1558	1.42	1.07
Specimens	43	30	22	22

2.3 Execution of the tests

The monotonic tests were performed at the Laboratory of Materials and Structures of the Solid Mechanics Group at Civil Engineering School of Ciudad Real (University of Castilla-La Mancha, Spain) between January and March 2023. The tests were run in displacement control with the guidance of the LVDT at the hydraulic jack application point. Four complementary vertical LVDTs characterized the deflection shapes, including measurement of the settlement of the neoprene supports. Additional LVDTs were fixed on the specimen to measure relative horizontal dis-placement (slip) between the steel profile and the concrete at the support. Strain gauges were placed on the steel profile and on the concrete.

Digital image correlation (DIC) was foreseen in the central section of the beam as well as on the supports. This was done by applying a pattern on the side of the beam, permitting to detect the crack initiation and growth; the same procedure has been applied on specimens of modified Brazilian test and is described in [16]. Due to limited space in this article only the results linked with load and displacement will be presented, but a complete report of the experimental results will be disclosed in future publications.

The tests were run up to failure of the beams with a plastic hinge forming in the centre of the specimen under the applied load. The tests under sagging or hogging moment had a similar setup and test execution. Two of the tests (one in sagging, one in hogging) were run considering relaxation, meaning including several steps in the loading procedure with considerable waiting time to account for load redistribution.

3. Experimental results

Following observations can be resumed:

- The tests have run according to the expectations, showing mainly a uniaxial bending behaviour without significant parasite effects.
- Tests have reached a considerable mid-span deflection level (minimal L / 45 for hogging, minimal L / 35 for sagging) before recording a load decrease.
- The load decrease is linked with the rupture of the longitudinal bars reaching their tensile resistance after yielding. This phenomenon is coherent for all tests both in sagging and hogging, except the first one where no rebar rupture and no load decrease was detected (this test was stopped at L / 25). The rebar breakages have not created a cross-section failure since both SFRC in compression and the structural profile was still integer could carry load further.
- No longitudinal slip has occurred between steel profile and concrete.

4. Numerical cross-section model

The experimental curves were compared with cross-section model (see Fig. 5) based on the direct integration of a cross-section fibre-model with the following assumptions:

- Bernoulli hypothesis of plane cross-sections.
- Stress-strain non-linear laws from prEC2 [2] for concrete and simple bilinear elastic-plastic relationship for structural steel.
- Steel characteristic values for yield strength (f_y = 480 MPa, f_{yk} = 624 MPa), and nominal values for the Young Modulus E_a= 210 GPa, E_s=200 GPa.
- Concrete average value for compression (f_{cm}=54 MPa) and tension as well as for Young Modulus E_{cm}= 33.5 GPa.

The correspondence concerning the sagging bending moment is very good. For hogging bending moment instead, the analytical model tends to underestimate the real behaviour because of the conservative stress-strain law.

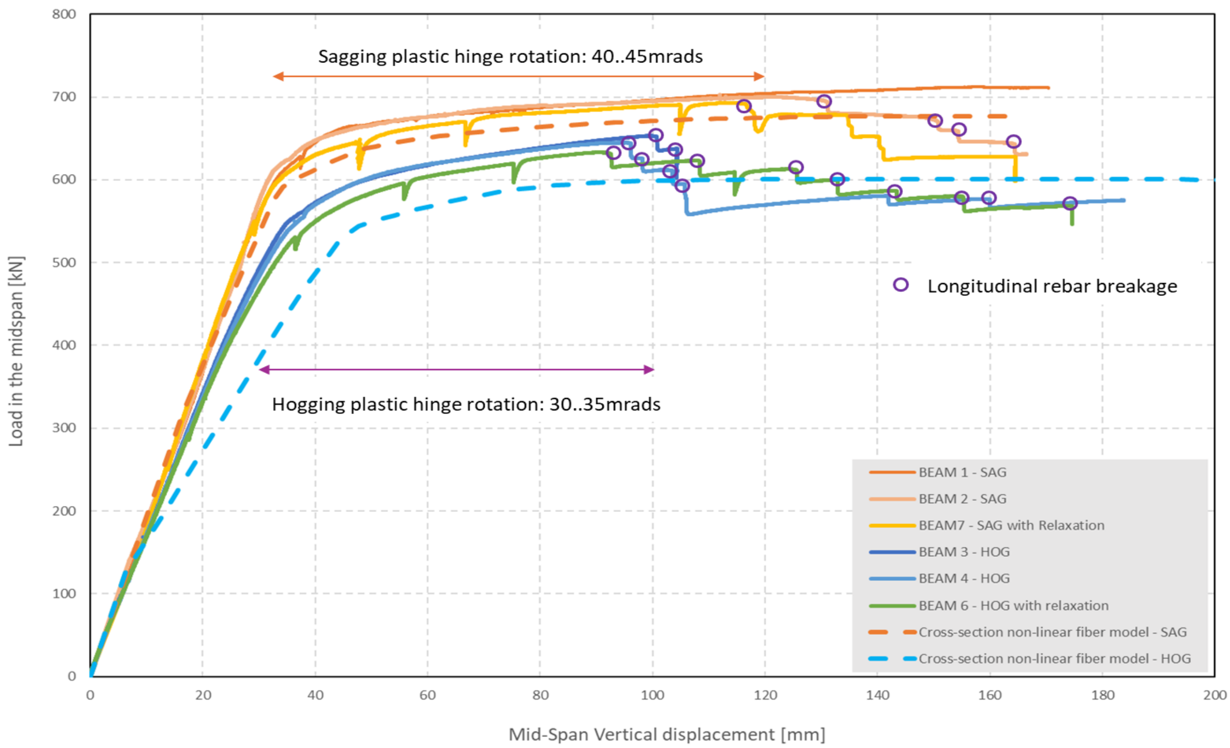

Fig. 5. Experimental load-displacement curves and comparison with numerical fiber model

5. Comparison between RC and SFRC

In the frame of this project it was decided to test all the beams with SFRC. The option to have specimens instead with plain concrete and with SFRC was initially considered but then disregarded due to budget reasons. Such comparisons permit a direct interpretation but, in this case, wouldn't have contributed to the final objective which was to study the use of the stress-strain relationship for SFRC for steel-concrete composite sections. Eventual good results with plain concrete due to a combination of good mixture and other conditions wouldn't have led to reconsider the constitutive law of the material or its use in the cross-section calculation. The difference between plain concrete and SFRC in term of ductility and tensile properties was studied at the coupon level (cylinders and cubes), where the differences found was in line with the code [2]. The results of the cylinder compression test on the concrete mix without fibres are showed in Figure 6.

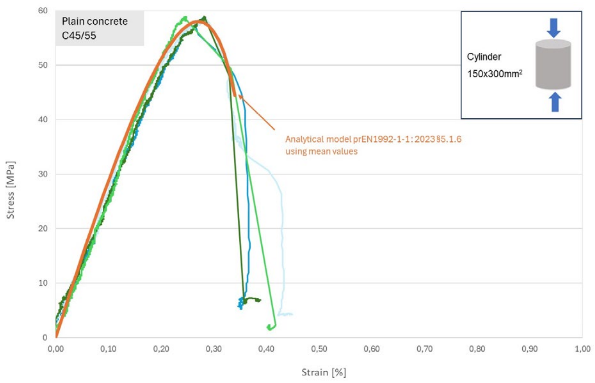

Fig. 6. Cylinder compression test on the same mix used for the test but without fibers

The comparison between the RC section and the SFRC section is done via a numerical model using the Eurocode 2 [2] ane Eurocode 4 [7] provisions, using design values and partial safety factor. The cross-section of the test has been used for this comparison.

The cross-section resistance is calculated with simple numerical model whereas the section is discretized into a fine mesh of strips, each of the elements having assigned a non-linear stress-strain curve depending on the material. The Bernoulli assumption of remaining of plane section is taken and the resulting internal actions are calculated by integration of the contribution of each strip for the given curvature, whereas the equilibrium for the normal forcé is imposed.

This model is analogous to the one used to recalculate the test mentioned previously, the only difference is that in this case design values instead of average measured values and partial safety factor have been used (therefore it can be seen the difference of approximately 20% between the mínimum bending resistance measured in the test and the design bending resistance).

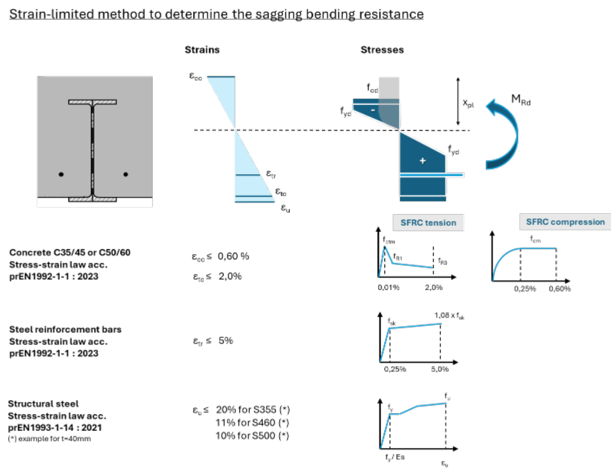

Fig. 7. Numerical model used for the comparison

The results are reported in Table 3 and show that for the case of the test the gain in term of bending resistance is limited, whereas the increase is mainly in the maximal section curvature (and consequently plastic hinge rotation) that the cross-section can develop.

Table 3. RC vs SFCR bending resistance

Component	RC	SFRC	Gain	Min test
MRd. Sagging [kNm]	565	585	*+3.5%*	693
Max section curvature Sag [1/m]	3.01%	5.54%	*+84.1%*	
MRd. Hogging [kNm]	-516	-528	*+2.3%*	631
Max section curvature Hog [1/m]	- 6.18%	-7.76%	*+25.6%*	

It shall be stressed that the benefits of using SFRC in term of bending resistance gain is proportional with the depht of the neutral axis in the composite section. In fact with deep-lying neutral axis, the maximum cross-section curvature is limited by the maximum compression strain in the concrete. SFRC allows much higher compression strains, allowing larger cross-section curvatures. This feature is key for shallow composite cross-section as it permits a complete yielding of the steel Profile, allowing to reach.

As in the Engineering practice is not suitable to perform non linear cross section calculations for all composite constructions, the code provisions have foreseen a specific reduction factor to be applied on the stress-block plastic bending resistance calculation to account. This factor is linked to the steel grade and the depth of the neutral axis.

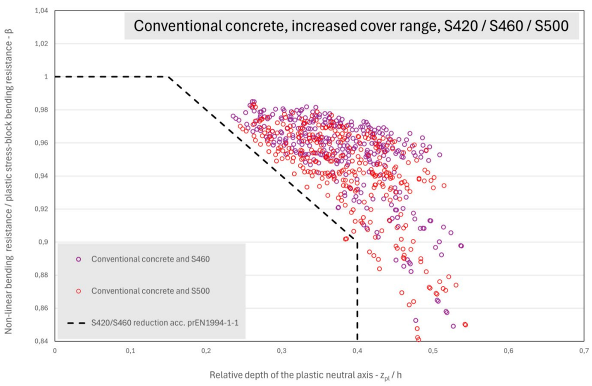

Fig. 8. Normative reduction factor of the plastic bending resistance for RC filler beam sections

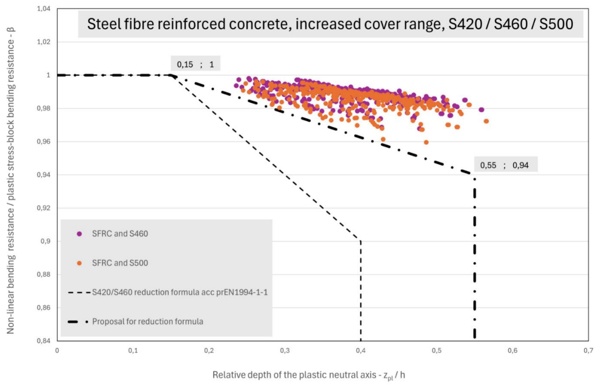

Fig. 9. Proposed reduction factor of the plastic bending resistance for SFRC filler beam sections

Recent work by the authours [17] have showed that the use of SFRC allows for a significant improvement of this reduction factor. Beside an improvement, SFRC makes also possible a larger range of cross-sections with deep-lying neutral axis, which becomes more and more requested for the realization of very slender overpass decks as replacement of existing old decks.

6. Conclusions

The paper presents the experimental results of monotonic bending tests performed on composite beams with encased steel profiles and SFRC in the aim to improve the ultimate bending resistance as well as the bending stiffness in serviceability phase. The results show a good correspondence of the experimental curves to a prediction by a non-linear fiber model using the stress-strain relationship from the codes.

In the tests the cause for the load decrease after resistance peak has been the tensile rupture of the longitudinal rebars. This has occurred with considerable high rotation in the plastic hinges after yielding and after severe damage caused in the section. Common rebars were used without special ductility requirements (whereas for seismic ductile design where high rotation capacity is required high ductility rebars are used).

These experimental have been used to validate a numerical model for parametric studies with the objective to assess specific analytical rules for the design of filler beam sections with SFRC; such Works are currently under publication [17].

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