Influence of test methodology on the applicability of test results of fibre reinforced concrete for design

Karoly Peter Juhasz[1], Peter Schaul[2], Dr. Ralf Winterberg[3]

[1] : Budapest University of Technology and Economics, Department of Mechanics, Materials & Structures, Műegyetem rakpart 1-3, Budapest, Hungary

[2] : Budapest University of Technology and Economics, Department of Construction Materials and Technologies, Műegyetem rakpart 1-3, Budapest, Hungary

[3] : EPC Holdings Pty Ltd, Singapore

Abstract

The design of fibre reinforced shotcrete (FRS) linings is commonly based on the Q-System or Barton charts. This performance based design approach accesses the results of experimental tests, carried out on panel specimens according to existing standards or guidelines. This is different to the general methodology to access and determine the performance of fibre reinforced concrete (FRC) using standardised beam tests.

Panel and beam test results yield significantly different information on the performance of FRC and it is problematic to correlate them. The beam test yields a stress-strain relationship for a small displacement range only. Based on the significantly different working and failure mechanisms, structural tests to evaluate the post-crack performance and the ductility of FRS linings are typically conducted on different types of panels rather than on traditional beams. As a consequence, test results based on beam tests may lead to an overestimation of FRC performance in panels and vice versa. In order to avoid uneconomic designs the most appropriate material must be found using the most appropriate test methodology.

This paper discusses the difficulty in correlating test results obtained from beams and panels as well as the discrepancy in performance of different FRC using different test methodologies and aims to provide guidance on materials, testing and design.

Keywords

synthetic fibre, FEA, panel test, testing methods,

1 Introduction

The basis of the design for fibre reinforced shotcrete tunnel linings was stated in the middle of the 20th century. From these years the design procedure changed more from empirical to scientific, however the traditional and well-established recommendations will not be out of the daily practice. The basis of the shotcrete lining design was quantitative tables, like the Q-Chart. Nowadays, with advanced finite element software, the rock separation and layering can be modelled, and from the calculated stresses the necessary fibre reinforcement for the shotcrete can be determined.

The Q-system was developed for classification of rock masses and ground and for evaluating the requirements for support in tunnels or rock caverns. It was developed by the Norwegian Geotechnical Institute (NGI) in the middle of the '70-s, originally included a little more than 200 tunnel case histories, mainly from Scandinavia (Barton et al., 1974). The system was updated to include more than 1000 cases (Grimstad and Barton, 1993). It is a classification system for estimates of tunnel support, based on a numerical assessment of the rock mass quality using several parameters. To get the overall rock mass quality a formula with three different quotients can be used, where the first parameters represent the relative measure of the rock size, the second quotient is described as an indicator of the inter-block shear strength, and the third quotient is described as the active stresses. The formula can be seen below:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

where:

- RQD: Rock quality designation (degree of jointing)
- J_n: Number of joint sets
- J_r: Roughness of the most unfavourable joint or discontinuity
- J_a: Joint alteration number
- J_w: Joint water reduction factor
- *SRF*: Stress reduction factor

From the Q value groups can be made to categorize the ground according to the rock mass quality. If the capacity of the rock is not sufficient, a common strengthening is to use fibre reinforced shotcrete and bolting. To define the necessary fibre reinforcement the energy absorption of the fibre reinforced shotcrete must be determined. This parameter can be obtained by means of panel tests (square or round), i.e. by measuring the middle point deflection and the reaction force. A further detailed overview on the design of fibre reinforced shotcrete linings is given in Nitschke and Winterberg (2016).

There are several recommendations for panel tests based on the geometry of the panel, the loading supports and the method of the loading. In Europe the basis of the panel tests were the recommendations of EFNARC (1996). Nowadays we use the harmonized European panel testing standard EN 14488-5:2006, which also employs a 600×600×100 mm centrally loaded square panel, but is supported by a continuous 20 mm wide steel frame.

In North America and in Australia round determinate panel (RDP) tests according to ASTM C 1550 (2012) are carried out, using a 75 mm thick panel with a diameter of 800 mm on three-point pivoted supports. To obtain a better fibre distribution and to reduce variability it is also possible to do super-size round panels with a diameter of 1200 mm and a thickness of 150 mm. These different panel tests all have in common that the specimens should be sprayed at the site and are not externally or internally compacted. For comparison, cast specimens that are compacted by vibration can also be used.

To design tunnels with Finite Element Analysis (FEA) software the measured energy absorption values are not sufficient; it is required to determine different concrete-specific and fibre reinforced concrete-specific parameters as well. One of the key parameters is the residual flexural strength, which describes and quantifies the fibre effect in the concrete. This parameter can be determined by using the harmonized European beam test EN 14651:2005, measuring the load vs. the crack mouth opening displacement (CMOD). This is a three-point bending test with a notch in the centre of the beam span. Material parameters can be gained from the residual flexural strength values according to different guidelines (Model Code 2010, 2012; RILEM, 2003; OVBB, 2008; ACI 544, 1999) which can be used in calculations.

The process of a panel test is relatively quicker compared to a beam test, with a lower variability of results. The beam tests need more preparation and the results could be misleading because of limited crack propagation and the variability is usually high with COV’s up to over 30%. There are methods to reduce the variability, but this makes the tests even more complex (Juhasz, 2015). Similar research has been done by Bernard (Bernard, 2002) comparing beam and panel tests (square and round panels).

Laboratory research is presented in this paper, where panels and beams were tested. Results were compared and a numerical FEA model was made to estimate the results of both types of test with the same material model parameters. The possibility of estimating the material parameters from panel tests was then examined.

2 Laboratory test

2.1 Test matrix

Sprayed panels and cast beams were produced to complete the previously presented test matrix (Juhasz et al., 2017). With this the results of plain concrete and FRC using three dosages of macro synthetic fibres (BarChip 48) were completed using one typical shotcrete fibre (BarChip 54). For the new series, three square panels and three beams were made. The specimens were produced in a tunnel jobsite in Poland and the test was carried out at the Adolf Czako Laboratory of the Department of Mechanics, Materials & Structures, Budapest University of Technology and Economics. The tests were conducted using a Zwick Z150 universal testing machine with a capacity of 150 kN. The test matrix can be seen in Table 1, with the new series in the right-most shaded column.

For the tests a sprayed concrete mixture was designed. The beams and the panels used the same mix design. The panels were sprayed and the beams were cast at the field. The macro synthetic fibre was BarChip 54 with 3.0 kg/m^3 dosage. The fibre length is 54 mm, it is continuously embossed and has a minimum tensile strength of 640 MPa.

Table 1: Test matrix

Fibre dosage	Plain concrete	2.5 kg/m^3 BC48	5.0 kg/m^3 BC48	7.5 kg/m^3 BC48	3.0 kg/m^3 BC54
Square panels	SQ PC 1-3	SQ 2.5 1-3	SQ 5.0 1-3	SQ 7.5 1-3	SQ 3.0 1-3
	cast	cast	cast	cast	sprayed
Beams	B PC 1-4	B 2.5 1-4	B 5.0 1-4	B 7.5 1-4	B 3.0 1-3
	cast	cast	cast	cast	cast

The beam and the panel test specimens were all stored under water according to EN 12390-3 and EN 14488-5. The specimens' testing date was at the age of 28 days.

2.2 Testing methods

The panel tests were carried out according to the EN 14488-5 standard. The geometry of the specimen was 600×600 mm with 100 mm thickness. The panels were tested on a steel support frame according to the standard mentioned above (see Figure 1).

A levelling mortar layer was applied between the sample and both the loading block and the square support frame. The test was displacement controlled with a speed of 1 mm per minute. The load-deflection curve was recorded and the test was continued until a deflection of at least 30 mm was reached at the centre point of the slab. This also allows to investigate the fibre effects in larger crack widths.

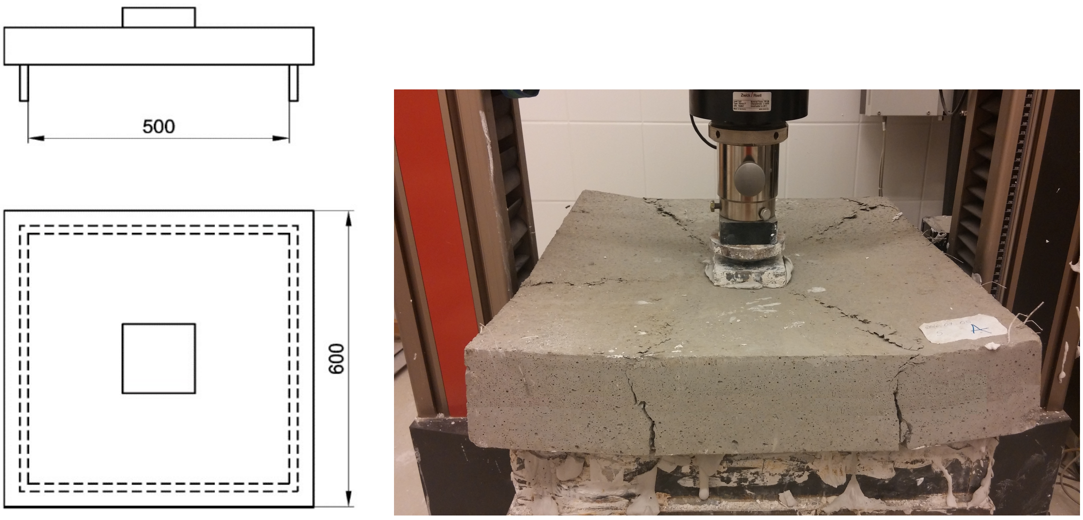


Figure 1. Setup of panel test according to EN 14488-5:2006

Beam testing was similar to the specification of EN 14488-3:2006. The test was a four point bending test of the macro synthetic FRC specimens with a length of 700 mm, cross-section of 150×150 mm on 450 mm span). The loading of the beam was in the third points of the beam. The testing machine used was the same deflection controlled universal testing machine used for the panel tests. The testing speed was 0.25 mm/min up to 0.5 mm centre point deflection, and 1.0 mm/min thereafter. The test was continued out to 4 mm deflection. The load and the centre point displacement were recorded during the test.

3 Test results

The square panel test results can be seen in Figure 2 and the beam test results in Figure 3. Compared to the previous research (see Figures 4 and 5) the sprayed panel results had a larger dispersion, and also the tests with the four point beams led to a higher variability. It can be also seen that the dispersion of the post-crack beam results are significantly higher than in case of the panels. The resulting crack patterns of the panels were absolutely different, depending on the fibre dose rate (see Figure 6). The general post-crack behaviour of the panels and the beams is similar: after the peak load a small drop can be seen and after this the fibres engage and provide a stable performance.

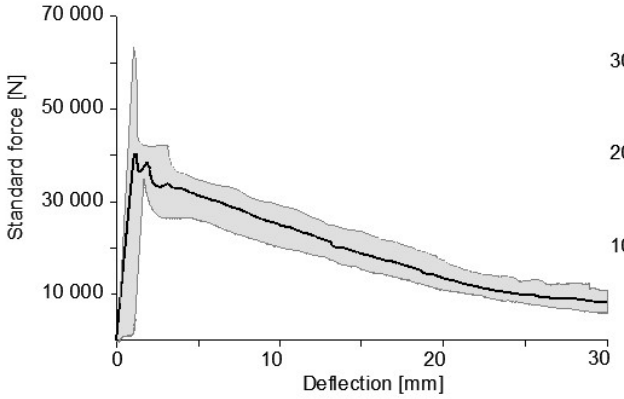


Figure 2. Sprayed square panel test results

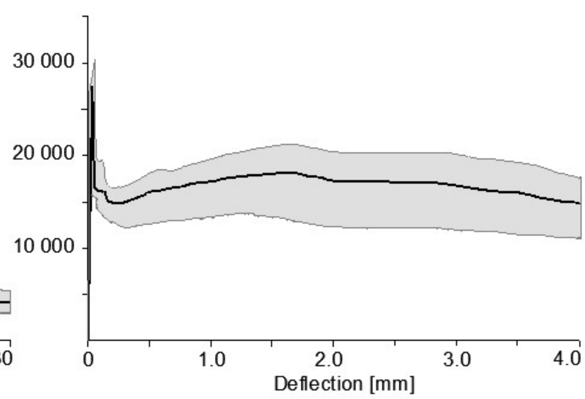


Figure 3. Cast beam test results

Due to the high variability the mean values of the beam results are not normative and the results had to be modified. To calculate a modified mean value, after the test the number of the fibres on the cracked cross section was counted in five different layers. With this method developed by Juhász (Juhasz, 2013) the effect of fibre orientation and the improper location are eliminated from the results. This modified mean value better represents the real capacity of the fibres.

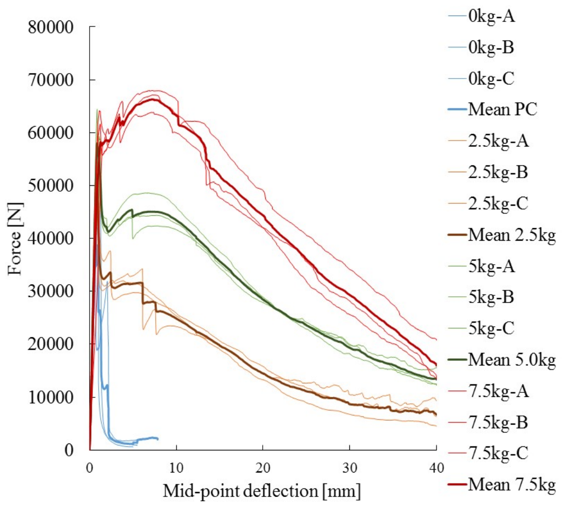


Figure 4. Poured square panel test results

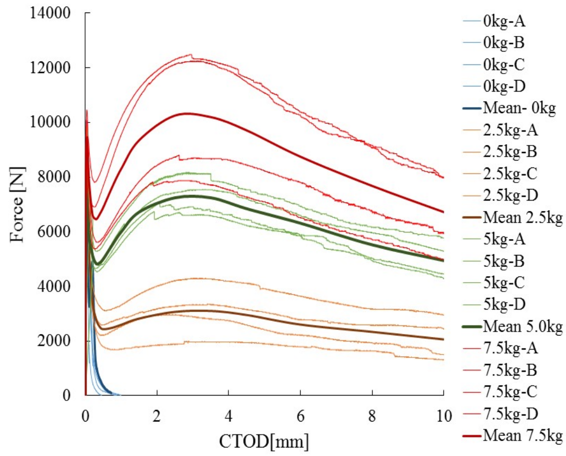
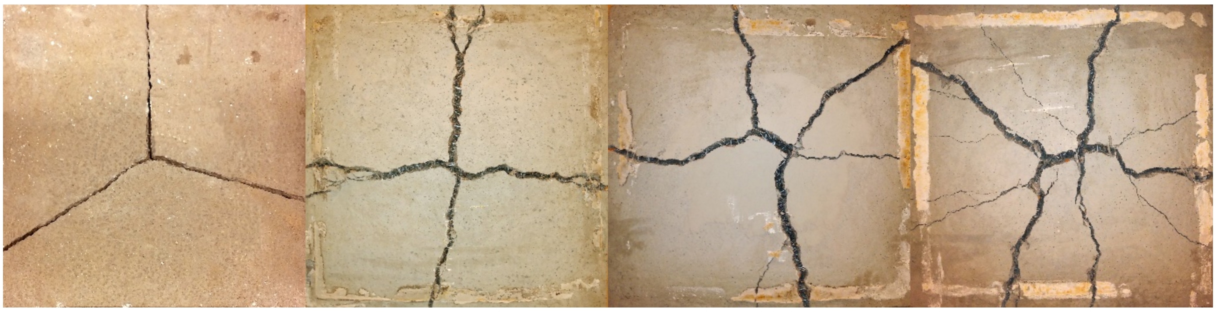


Figure 5. Cast beam test results

As can be seen from Figure 6 the crack development in the panels was different for every dosage. By raising the dosage of fibres in the concrete more and more cracks appear. To compare the effect of the fibres with different dosages the area under the load-deflection curve in the case of panels, and the area under the load-CMOD diagram, can be calculated.

Due to their different working mechanism, the correlation between panel and beam tests can't be formulated directly, but the test could be modelled using advanced Finite Element Analysis (FEA).



Plain concrete 2.5 kg 5.0 kg 7.5 kg

Figure 6. Ultimate crack patterns of the panels

4 Numerical modelling

4.1 Material model of concrete and FRC

The behaviour of FRC material is analysed using ATENA (Cervenka et al., 2016) for non-linear analysis of concrete structures. ATENA is capable of a realistic simulation of concrete behaviour in the entire loading range with ductile as well as brittle failure modes as shown for instance in (Cervenka, 2002). It is based on the finite element method and non-linear material models for concrete, reinforcement and their interaction. The tensile behaviour of concrete is described by smeared cracks, crack band and fracture energy and the compressive behaviour of concrete by a plasticity model with hardening and softening. The constitutive model is described in detail in (Cervenka & Papanikolaou, 2008). The non-linear solution is performed incrementally with equilibrium iterations in each load step. Numerous other models can be used to approximate the post-cracking capacity of FRC. The model presented in the ITAtech guideline (ITAtech Activity Group Support, 2016) was used here.

A thin band with micro-cracks will appear due to the tensile stress in the concrete – which is called the crack process zone. By increasing the stress the concrete reaches its tensile strength when the micro cracks are touching each other. After this point the tensile capacity of the concrete will decrease, the cracks will bypass or cross the aggregates and then the entire section will be crossed by a macro crack. The area under the "tensile stress – crack width" diagram is the fracture energy.

The fracture energy of the concrete is influenced by a number of factors which are clearly not related to the concrete's strength class. Most of the existing design methods neglect the fracture energy of the concrete and do not pay much attention to the tensile strength. However, when designing FRC structures these parameters cannot be ignored.

The main goal in this method is to separate the fracture energy of the concrete (G_F) and added fracture energy by the fibres (G_{Ff}). According to previous research (Juhász, 2015) the added fracture energy depends on the fibre type, dosage and cement mortar (cement, water and sand). By knowing these values the added fracture energy can be defined and used as a parameter partly independent from the concrete.

The most sophisticated model of FRC material represents an extension to the fracture-plastic constitutive law (Cervenka & Papanikolaou, 2008). It describes the tensile behaviour according to the material response measured in tests point-wise in terms of the stress-strain relationship. The first part of the diagram is the usual stress-strain constitutive law. After exceeding the localization strain ε_{loc} the material law assumed for the characteristic crack band width L_{ch} is adjusted to the actual crack band width L_t. The characteristic crack band width (characteristic length) is the size (length) for which the defined material law is valid. The same procedure (with eventually different characteristic length) is used for the compression part of the material law. The softening law in compression is linearly descending and the end point of the softening curve is defined by the plastic displacement w_d. By increasing the material parameter w_d the contribution of the fibres to the compressive behaviour of concrete is considered. Another important parameter for FRC modelling is the reduction of the compressive strength due to developing cracks that determine how the strength is reduced while the material is subjected to lateral tension.

The numerical verification was made using ATENA. To get a proper result the full experimental setup had to be modelled, including the loading device, the supports and the levelling mortar layer. To be able to model the curling rise of the panel's corners from the steel formwork, a non-linear interface material was applied between the concrete panel and the centrally located steel loading plate.

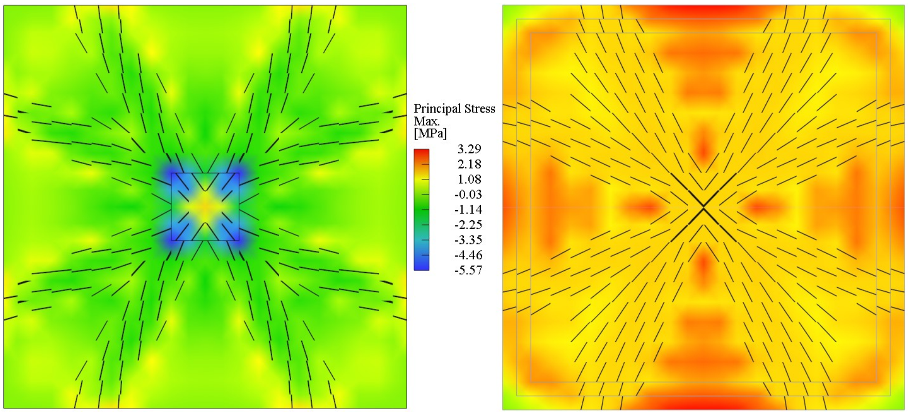


Figure 7. Numerical model of the panel with upper surface (left) and bottom surface (right)

The material parameter of this layer was adjusted as for the parameters of the mortar layer. The compressive strength of the interface layer was 10-times higher than the shear and tension capacity. The virtual test was displacement controlled to be able to model the post-crack behaviour of the panel. During the analysis the mid-point deflection and the reaction force was measured.

Structural hexahedra mesh was used in the model to obtain the proper crack propagation. The size of the brick elements was 25 mm in every case. Figure 7 shows the principal stress and cracks of the panel when modelled by FEA (upper surface of the panel on the left and lower surface on the right). The material parameters used were determined by inverse analysis.

5 Results of the numerical model

The mean values of the tests and the numerical results of the panels can be seen in Figure 8a.

The behaviour and value of the numerical model closely matches the test results for each dosage of fibre. The peak load is almost the same, and the slope of the curve from FEA is close to the test curve for each fibre dosage. Note that the maximum difference in the areas under the curves was only 7%.

Using the same material parameters the beam tests were modelled with ATENA and the results can be seen in Figure 8b. The differences in the areas under the curves range from 4% to 18% using modified mean values, and 4% to 10% using mean values.

Material parameters can be derived from panel tests, where there is much lower variability of the results than for beam tests. The residual strength parameter is a function of the fibre dosage, which produced a nearly linear function in the test series. Using FEA a correlation can be made between the dosage of fibres and their performance. Even using a linear residual strength model the correlation is acceptable, leading to a proper material model.

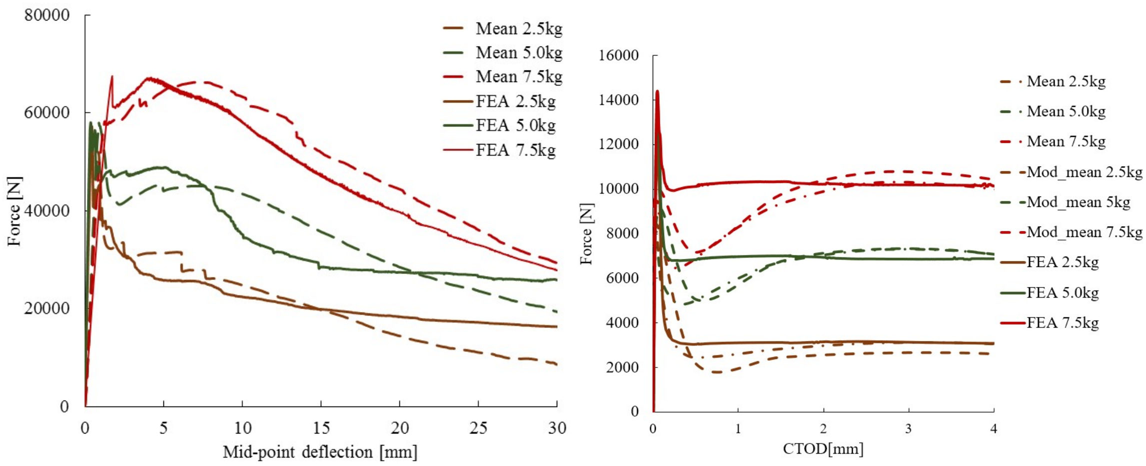


Figure 8. Results of the panel (a) and beam tests (b) with their modelling by FEA

6 Conclusion

Macro synthetic fibre reinforced concrete structures are becoming more common in the tunnelling industry, especially in shotcrete tunnel linings. Both for the design and for their calculation the performance of the fibres in the concrete has to be determined. The current tests used in Europe are the square panel test and the three point bending beam test which define the fibre reinforced concrete's post crack performance. Beam tests are more common to designers, although they have an inherent high variability. Square panel tests provide a more favourable variability, but the material parameters cannot be directly obtained from their results so far. However, the square panel test results can be used to determine the fibre reinforced concrete energy absorption which can be applied in the design with the Q-Chart.

To try to find a correlation between fibre reinforced concrete panel and beam tests, a laboratory test series was carried out using a typically used sprayed concrete mixture and both beams and panels were cast with different dosages of macro synthetic fibres. According to the results a direct correlation cannot be found between the two different testing methods because of the different working and failure mechanisms: while in the case of square panels the number of cracks increases with an increase in the amount of fibres added, opposed to the beam tests where there is only one crack located in the centre of the beam due to strain localization in a static determinate setup.

A numerical model was developed to be able to do further calculations from the panel results. A finite element material model was defined for all square panel tests with an inverse analysis calculation undertaken which well corresponds to the area under the individual load-deflection curves. This defined material model is capable of calculating the beam performance using the same material properties and thus, the further calculation and design became possible. It could be useful for design engineers to verify a material model using only panel tests. Further research is planned to determine the performance of different fibres in panels and beams and to compile a database for design engineers with the test results.

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