IMPACT RESISTANCE OF LOAD BEARING SANDWICH ELEMENTS WITH TEXTILE REINFORCED CONCRETE FACES

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ABSTRACT

Textile reinforced concrete (TRC) is a recently developed type of glass fibre reinforced concrete. The aim of this paper is to show the potential of TRC for low-speed impact. Therefore, series of impacted TRC laminates are subjected to several post-impact analysis techniques: visual interpretation of cracks, digital image correlation and analysis of post-impact stress strain curves. These post-impact tests provide valuable information on the damage mechanisms that occur during impact and on their effect on the remaining load-bearing capacity.

1. INTRODUCTION

Usually the aim of introducing fibres in cementitious materials consists of enhancing the energy absorption, toughness or crack distribution. Fibres are usually introduced into the concrete mixture by procedures like mixing and casting, pressure forming or in the form of shotcrete. Only a limited amount of fibres (~1%) can be inserted this way, since clustering might occur when larger quantities of fibres are used. Another obvious disadvantage of the above-mentioned methods is the fact that it is not easy to obtain a homogeneous spatial distribution and also the orientation of the fibres is not easily controlled. In contrast to classical fibre reinforced concrete, textile reinforced concrete (TRC) - with woven textiles or chopped strand mats - offers a distinguished improvement of the load bearing capacity of cementitious materials because of the higher amount of fibres that can be introduced into the cementitious matrix (up to 15%, e.g. [1-3]). Moreover, the orientation and spatial distribution of the fibres in the matrix are well controlled. The main advantage of TRC is the increase of the load bearing capacity. Figure 1 shows illustrative stress-strain curves of FRC and TRC.

Given the low cost, combined with relatively high strength and stiffness and the fact that they are not liable to creep, glass fibre textiles seem to be an interesting reinforcement material for the use in cements. Another advantage of glass fibres is their small diameter (14 nm), which can result in a fine matrix cracking pattern, since the specific surface for stress transfer between matrix and fibres is large. Unfortunately, glass fibres have some disadvantages in a cementitious environment. Most of the cement types lead to a high pH in the concrete pores, which provokes an optimal environment for glass fibres to be attacked chemically. A solution described by Majumdar and Tallentire [4] to decelerate this ageing is the addition of approximately 16% in mass of zirconium to the glass fibres, which are denominated as AR-glass fibres (alkali resistant). Another solution consists of the use of cements with a lower pH. One of these cements is Inorganic Phosphate Cement (IPC) [5]. This cement shows a neutral pH after curing, which implicates that the fibres will be hardly attacked chemically [6].

With TRC it is possible to manufacture thin composite laminates which can be used as faces in sandwich elements [7], in freeform architecture [8] and for retro-fitting [9]. A new interesting application that is currently under study at the Vrije Universiteit Brussel is the use of TRC as a composite face of lightweight sandwich panels [10] that can be used to protect the underlying construction (building, bridge) against impact. The aim of the TRC laminate is mainly to transfer the energy from the external impact source towards the core in a more favourable – smeared and reduced – way towards the core. Preferably, the TRC face would also be capable to dissipate energy during impact, but without losing load bearing capacity since it mainly serves as buffer element.

The aim of this paper is to provide preliminary essential information on the effects of low-velocity impact on TRC. Several experimental series under low velocity impact are conducted and the occurring damage mechanisms are measured and discussed. By means of post-impact analyses, the laminates are studied and the damage mechanisms that appear during the impact test can be identified and described. The post-impact analysis comprises visual interpretation of damage (to obtain an idea on the pattern of matrix cracking at the surface), Digital Image Correlation (to measure the remaining deflections and crushing) and post-impact static tensile testing up to failure with subsequent analysis of the obtained curves. In earlier publications [11-21] essential information on occurring damage mechanisms in their identification in brittle matrix composites (like TRC) can be found. Globally, following mechanisms are identified:

- matrix cracking, with subsequent debonding between fibres and matrix and stabilisation of cracks by bridging of fibres
- further debonding and wear of interface between fibres and matrix
- delamination between neighbouring layers
- fibre failure or fibre pull out

Within the scope of this paper, these mechanisms will also be identified during and after impact testing. Since matrix cracking and interface debonding/wear are the damage mechanisms that do not necessarily lead to failure and since the residual strength is not necessarily affected; it is advantageous to provoke these mechanisms in favour of the other mechanisms.

2. EXPERIMENTS

2.1 Loading of virgin specimens

In compression, TRC can be considered a linear elastic material up to failure. In tension however it shows a nonlinear behaviour. Understanding of the behaviour of TRC under static tensile loading (and unloading) might provide a good basis for interpretation of TRC under low velocity impact. The tensile behaviour of TRC-composites will be described only globally, since it is described in several publications [11-17].

Within the stress-strain curve of brittle matrix composites, three different stages were identified (as shown in Figure 1) by Aveston et al., [11]. The theory was initially created for composites with unidirectional fibres. It was however later extended to include other fibre orientations (e.g. [12, 13]). According to this theory, a three-stage model, as shown in Figure 1, can be constructed. In the first stage (which is often referred to as the linear elastic stage), the fibre-matrix bond is globally adhesive of nature. The stiffness of the linear elastic stage (E_{cI}) can thus be described by the law of mixtures:

$$E_{cI} = E_f V_f + E_m V_m \quad (1)$$

where E_f and E_m are respectively the stiffness of fibres and matrix and V_f and V_m are the volume fractions of fibres and matrix. When not all fibres contribute equally to the load bearing capacity, V_f is often multiplied with an efficiency factor η_{el}.

Once the stress in the matrix exceeds the matrix strength, which is assumed to be deterministic, the multiple cracking stage is reached and a fine parallel crack pattern is formed. At the vicinity of each crack, the previously existing (adhesive) fibre-matrix stress transfer is replaced by friction. If the fibres are not too short, the amount of fibres is high enough and if the frictional shear stress between matrix and fibres is not too low, the fibres will bridge the crack and extra load can be applied. Within the multiple cracking stage, energy is dissipated through the formation of new free surfaces (matrix cracking and fibre-matrix debonding).

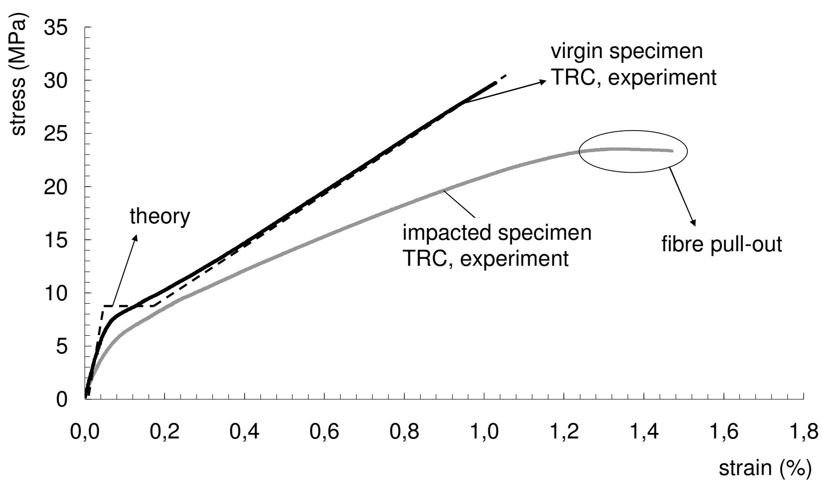

Figure 1: Illustrative nominal stress-strain curves for classical fibre reinforced concrete and textile reinforced concrete (before and after impact).

Beyond the multiple cracking stage, only the fibres will carry extra load. This third stage is called the post cracking stage and is characterized by the stiffness of the fibres (Figure 1). The stiffness in stage 3 can be globally written as:

$$E_{cIII} = E_f V_f \qquad (2)$$

When not all fibres contribute equally, V_f is often multiplied with a factor η_{pc}. As can be seen in Figure 1, the above-mentioned theory shows some discrepancy with the depicted experimental curve and this mainly in the multiple cracking stage. In reality matrix cracking appears with a certain stress range, and the above-mentioned model can be extended, including a stochastic distribution function, to model the effect of matrix multiple cracking in a more realistic way [13-17].

2.2 Tensile loading of virgin specimens: interpretation of post-impact behaviour

Figure 1 shows exemplary stress-strain curves obtained on a virgin specimen and on an impacted specimen. If the composite stiffness in the third stage is lower after impact, this is an indication that fibres were damaged or that the interface between matrix and fibres (or fibre bundles in this case) experienced deterioration, since the stiffness in the third stage is representative for the contribution of the fibres only (see Equation 2). Figure 1 also clearly shows that the initial stiffness of an impacted specimen (at low stresses) is much lower than that of a virgin specimen. If the effect of fibre damage (as determined on the post cracking stage) is not sufficient to explain the loss of stiffness in the first stage, it can reasonably be assumed that matrix cracking also occurred. This matrix cracking, which is introduced in a previous load step (e.g. impact), cannot be introduced explicitly within the above mentioned models and is explained in next section.

2.3 Tensile loading of specimens with previously induced damage

The behaviour of TRC specimens, that already suffered matrix cracking during previous loading ([6], [13], [18-21]) will be briefly explained. If a specimen already shows partial multiple cracking before a tensile test is applied, some regions of the specimen will still comprise an adhesive bond between fibres and matrix and behave linear elastic while other regions of the specimens (in the neighbourhood of matrix cracks) will already show a frictional stress transfer between matrix and fibres. In the neighbourhood of existing cracks, the fibres will slip out of the matrix upon initial loading. The length, along which this slip occurs, increases with increasing applied stress and the stiffness of the specimen will gradually decrease, even if no extra matrix cracks are formed (see e.g. [6], [13] and [18-21]). Based on [6], [13] and [18-21] a formulation was found expressing the secant slope (slopesecant) that can be measured between applied stress (σ_c) and resulting strain of a TRC specimen with existing matrix cracks. This formulation is only valid as long as no new cracks are introduced within the studied loading step and as long as the fibres do not slip completely out of the matrix:

$$slope_{\sec ant} = \frac{E_{cI}}{1 + \frac{E_m V_m r \alpha \sigma_c}{4x E_{cI} V_f^* \tau}} \tag{3}$$

Where:

- E_{cI} = stiffness in pre-cracking stage [MPa]
- $\alpha = E_m V_m / (E_f V_f^*)$ and $E_f V_f^*$ = stiffness in post-cracking stage
- r = fibre diameter [mm]
- τ = average matrix-fibre bundle shear stress transfer [MPa]
- x = average actual distance between existing neighbouring cracks [mm]

2.4 Tensile loading of specimens with previously induced damage: interpretation of post-impact behaviour

Equation 3 shows that, when a secant slope (slopesecant) is determined on a stress-strain curve with matrix cracks, the average distance between previously introduced neighbouring cracks (x) can be determined – as long as the corresponding applied stress (σ_c) did not lead to extra cracking. This method is further used in this paper.

3. TEST SET-UP AND POST-IMPACT ANALYSES

Impact tests are performed on relatively thin laminates of E-glass fibre random mats (2D-random chopped strand mat with 50mm fibre length; 300g/m²; Owens Corning) with the above-mentioned (see introduction) Inorganic Phosphate Cement (IPC) matrix [5]. The IPC matrix is chosen for two reasons:

- The curing process can be accelerated by heating to 60°C.
- The properties of the laminates are not function of the moment they are tested.

The impact test set-up used in this study is a drop weight tower with a steel ball of 880g as impactor. The laminates are clamped on two opposite sides. The drop height was 2.2m. Two series of laminates are tested in order to study the influence of the material parameters. The parameters that are altered are:

- The fibre volume fraction (with constant thickness)
- The thickness (with constant fibre volume fraction)

In Table 1 and 2 the produced laminates are listed together with their fibre volume fraction and average laminate thickness. Several post impact tests were carried out. First of all the plates were inspected visually. A solution of ink and water is spread out on the laminate to visualise the crack pattern in the matrix (Figure 2). Digital Image Correlation (DIC) was used to measure the residual deformations of the laminate and was used on the impacted side of the laminates.

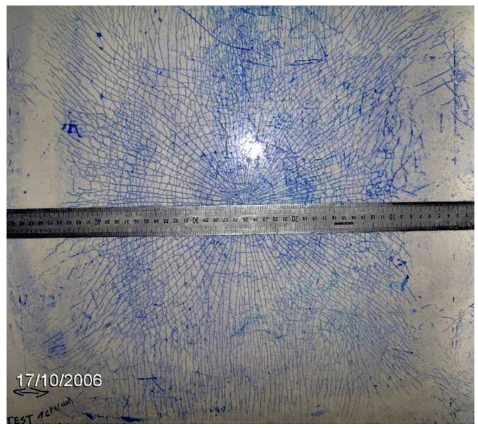

Figure 2: Crack pattern under low-speed impact and directions of principle stresses under static loading.

From the 3D-analysis of the remaining deformation of the plates, the global and local (crushing) deformations can be discussed. After the impact test is carried out, each laminate is cut in parallel segments of 25x500 mm² (width x length). These specimens were numbered and their distance to the impact point was listed. Subsequently, a tensile loading test is carried out by a tensile testing machine with a load cell of 10 kN and is displacement controlled with a speed of 1mm/min. An extensometer with base of 50 mm was placed on the specimens. Analysis of the post-impact behaviour (stress-stain curve) of the laminates can thus provide extra information on the damage mechanisms that occurred.

4. RESULTS

4.1 Effect of the fibre volume fraction

From the post-impact tensile testing the remaining strength at the point of impact was determined and the results are listed in Table 1. It can be seen in this table that the absolute strength reduction increases with increasing fibre volume fraction, while the loss of absolute composite stiffness in the post-cracking stage is similar for all tested plates. There could be two possible explanations for this behaviour: (1) some fibres are partially damaged during impact or (2) the interface between fibres and matrix is damaged and fibre pull-out occurs rather than fibre fracture.

Figure 3a shows the remaining out-of-plane displacements as measured by DIC after impact. In order to have a better appreciation on the damage at the impact location, the curves are shifted and the point of impact is taken as a reference (Figure 3b). Figure 3a shows that all plates are subjected to remaining global deflections and also show more severe local damage at the point of impact. A similar effect was noticed from the evolution of the residual strength of the plates. While no obvious strength loss was noticed in the rest of the plate, a 20-30% strength reduction was measured at the impact location (see table 1). Two mechanisms could explain these effects: (1) fibres are damaged at the impact location or (2) the matrix is damaged profoundly leading to subsequent loss of matrix-fibre stress transfer. Figure 1 supports the second explanation. Although the virgin specimen showed sudden fracture of the composite – typical for fibre fracture – the post-impact stress-strain curves obtained on the specimens at the impact zone show behaviour at failure, which is typical for fibre pull-out. Figure 3b also shows that it is not very likely that the most upper layer of fibres is directly crushed. Even if it is assumed that the depth of the locally measured pits (0.30 mm) is completely due to crushing of the upward side of the laminate, the upper fibre layer is not affected directly, since it is positioned at 0.40mm from the surface at least.

Table 1: Stiffness and strength before and after impact (at point of impact): influence of fibre volume fraction and influence of thickness.

Vf (%)	Virgin specimen		Impacted		Reduction of strength		Reduction of stiffness		
	tensile strength (MPa)	E_{III} (GPa)	tensile strength (MPa)	E_{III} (GPa)	Abs. (MPa)	Rel. (%)	Abs. (GPa)	Rel. (%)	crack density (%)
12,6	38	3,2	27	2,7	11	28	0,5	15	450
11,2	33	2,7	24	2,2	9	27	0,5	19	220
10,3	35	2,7	26	2,2	9	26	0,5	18	160
9,90	29	2,3	22	1,6	7	25	0,7	29	100
8,28	25	1,9	20	1,4	5	19	0,4	23	69

Visual interpretation of the matrix cracking revealed that the global density of cracks along the whole plate was higher for the plates with higher fibre volume fraction. Around the point of impact, the cracking pattern was determined in a semi-numerical way. The post-impact stress-strain curve of the specimens that contained the impact point obviously showed lower 'initial' stiffness (at low tensile stresses). The post-impact stress-strain curve of the specimens that contained the impact point obviously showed lower 'initial' stiffness (at low tensile stresses). In sections 2.3 and 2.4 it was explained how the amount of existing matrix cracking can be back-calculated from a new stress-strain experiment. The results are of course not to be interpreted as absolute numbers: the matrix cracks that occur under impact are not all aligned parallel to the load that is applied during the post-impact tension test. The plate with 9,90 % of fibres will thus be used as a reference plate and matrix cracking in the other plates will be calculated relatively to this reference. The results are listed in Table 1 and show that the crack density increases with increasing fibre volume fraction. Generally, a higher fibre volume fraction will lead to more (but finer) cracks [10-17]. Analysis of the specimens further away from the point of impact confirmed the same trend. The introduction of a higher fibre volume fraction therefore seems to dissipate more energy through the formation of new free surfaces in the matrix without consequently leading to a much higher loss of strength.

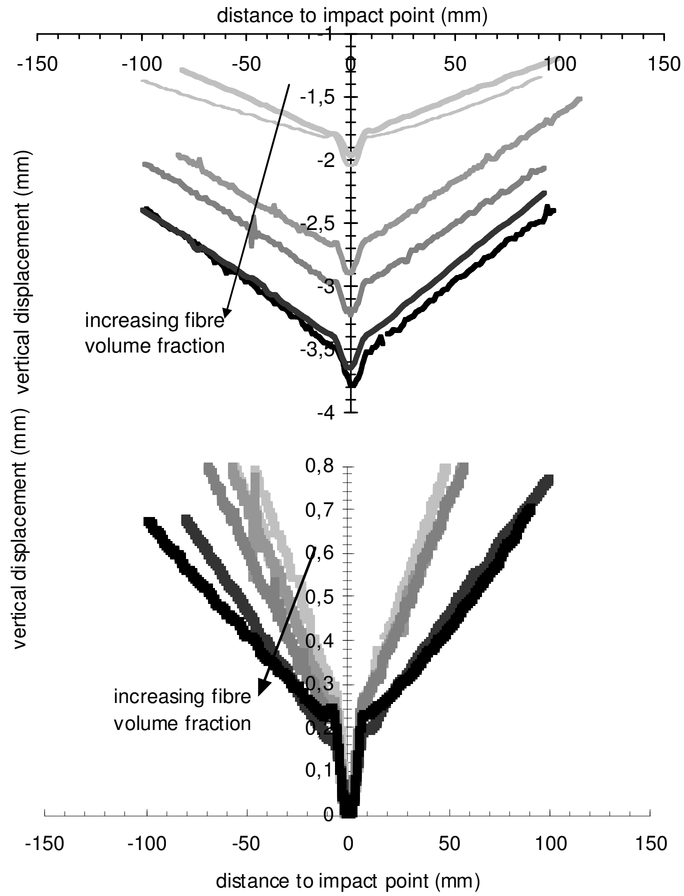

Figure 3: residual deformation of plates after impact (from digital image correlation): effect of fibre volume fraction.

4.2 Effect of the thickness of the laminates

The thickness of the laminates is the second parameter under study. Table 2 shows the failure stress and stiffness in the third stage as determined on the stress-strain curve under post-impact tension. From this table, one can conclude that the amount of fibres that is damaged at the point of impact seems to be higher when the thickness of the laminates is higher.

Table 2: Stiffness and strength before and after impact (at point of impact): influence of fibre volume fraction and influence of thickness

# layers	Virgin specimen		Impacted		Reduction of strength		Reduction of stiffness		
	tensile strength (MPa)	E_{III} (GPa)	tensile strength (MPa)	E_{III} (GPa)	Abs. (MPa)	Rel. (%)	Abs. (GPa)	Rel. (%)	crack density (%)
4	29	2,3	22	1,6	7	25	0,7	29	450
8	33	2,2	20	1,6	13	39	0,6	27	220
10	33	2,6	16	1,5	17	52	1,1	41	160
12	32	2,9	20	1,6	13	39	1,3	45	100
4	29	2,3	22	1,6	7	25	0,7	29	69

Figure 4a shows the out-of-plane displacements of the laminates. Figure 4b shows the same curves, but shifted to the impact point and clearly shows that deeper crushing occurred when more layers were used. A possible explanation could be that the global stiffness of these laminates was higher and lead to a shorter impact time.

The relative matrix cracking was calculated in the same way as in the previous section and the results are depicted in Table 2. Globally, the thicker laminates show less matrix cracking compared to the thinner reference laminate. This might be an indication that the damage mechanisms that are considered to be favourable - since they lead to energy dissipation, without necessarily leading to loss of strength - are not developed to the full extend. For a similar equivalent static load, thinner laminates will globally develop a finer crack pattern at the bottom of the laminate, since the stresses will be higher. Although the stiffer laminates will in reality be subjected to a higher equivalent quasi-static point load, due to the shorter impact time, this seems not to overrule the previously explained effect within the tested series.

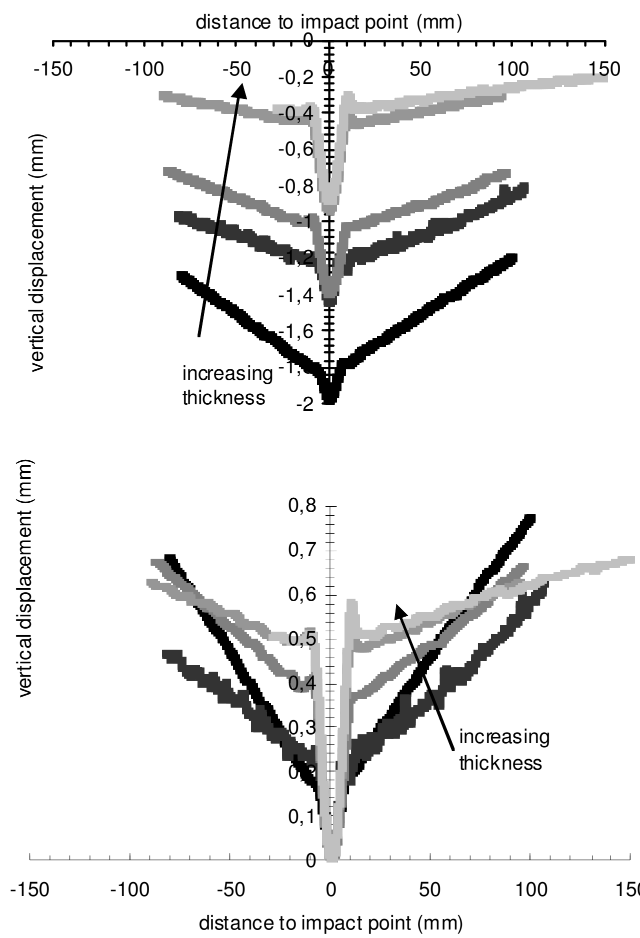

Figure 4: residual deformation of plates after impact (from digital image correlation): effect of thickness of laminates.

5. CONCLUSIONS

The aim of this paper was to show the potential of textile reinforced concrete (TRC) to dissipate energy under low-velocity impact. Two series of TRC laminates were tested under low-speed impact. Visual crack interpretation, digital image correlation and post-impact tensile loading were used to study the occurrence of damage mechanisms under low-velocity impact. The effect of increasing fibre volume fraction and increasing thickness was tested and discussed this way globally (for the whole plate) and locally (at the point of impact).

Globally, residual deflections were measured for all plates and found to be due to matrix cracking, matrix-fibre interface debonding and interface deterioration. Along the tested plates, energy was thus dissipated without leading to considerable global loss of strength. It was found that increasing fibre volume fraction and decreasing laminate thickness lead to a finer matrix cracking pattern and consequent higher global energy dissipation per layer.

Locally, at the point of impact, the strength after impact was systematically lower than the initial strength. It was found that an increasing fibre volume fraction and an increasing laminate thickness lead to higher loss of strength. Since the local crushing depth was similar for all specimens within the series of variable fibre volume fraction, it was concluded that the higher loss of strength with higher volume fractions is due to decreasing protective matrix layer thickness. The increasing loss of strength with increasing thickness was due to the fact that more energy was dissipated locally. Due to higher global stiffness, the equivalent quasi-static load was higher, leading to higher local crushing depths.

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