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STIFFNESS DEGRADATION AND FRACTURE BEHAVIOUR OF TEXTILE-REINFORCED CONCRETE UNDER QUASI-CYCLIC LOADING

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Abstract: Textile Reinforced Concrete (TRC) is a thin and lightweight cement-fibre composite material. In this study, the mechanical performance of TRC under quasi-cyclic loading is evaluated through an experimental program. TRC specimen of size 500 x 60 x 10 mm with four layers of AR-glass textile fibers were prepared and tested under uniaxial tensile quasi-cyclic loading. The load-deflection response and stiffness degradation are evaluated to understand the damage progression in TRC. The result indicates substantial stiffness degradation from 17% to 60% in Zone II due to multiple crack formation indicating an accelerated deterioration process. The combined DIC and AE analysis shows that matrix cracking and crack initiation cause dense and high-frequency AE activity up to the multiple cracking zone (<0.2% strain). As cracks stabilize, widen, and propagate at increasing strain, the density of AE events reduces.

1 INTRODUCTION

Textile Reinforced Concrete (TRC) is a new generation of fiber cement composites that offer several advantages over conventional steel-reinforced concrete systems [1]. TRC utilizes 2D or 3D textiles (e.g. carbon, glass, aramid) as continuous reinforcements. This enables the production of thin and lightweight structural components with improved load-bearing capacity and durability. Currently, the primary applications of TRC include the construction of facades, and retrofitting and strengthening of existing concrete structures. Since TRC does not contain conventional steel reinforcement, it is corrosion free, making it suitable for use in marine structures, stormwater drains, sewage treatment plants, and swimming pools [2,3].

TRC research has been predominantly focused on its mechanical and fracture behaviour under direct tension [4,5]. TRC under tension typically shows a three-stage response as shown in Figure 1. Stage I represents the phase up to the point where the first crack appears in the matrix. During this stage, the composite remains predominantly in an elastic state. Stage II involves multiple cracking, where the redistribution of stress leads to the formation of several cracks within the matrix. Finally, in Stage III, crack saturation is reached, and crack widening occurs. At this stage, the textile reinforcement takes on the full load, exhibiting strain-hardening behaviour. The response of TRC is often idealized as either a trilinear or bilinear curve, depending on the volume fraction of textile fibers. A bilinear response is typically observed when the volume fraction exceeds 3% [4]. In addition to the volume fraction, factors such as textile type, mesh size, and the number of layers have been shown to significantly influence the behavior of TRC.

With TRC spanning different applications, under cyclic loading conditions, it is important to assess its behaviour under cyclic loading conditions. While few researchers have studied the fatigue behaviour of TRC [5-13], to the author's knowledge, TRC’s behaviour under tensile quasi-cyclic loading has been explored by only one researcher [14]. In their research, the quasi-cyclic loading was applied at different displacement levels corresponding to the monotonic load-displacement curve. The findings revealed that over 50% of the stiffness reduction occurred immediately after the initial crack, suggesting that stiffness degradation is primarily associated with the progressive cracking of the TRC composite.

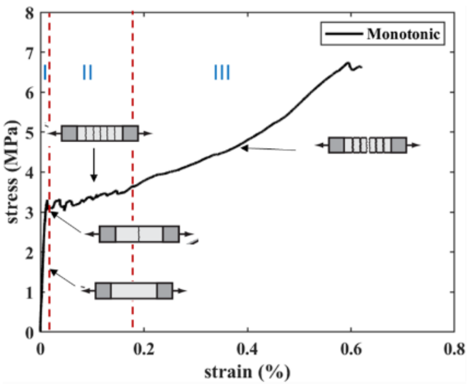

Figure 1. Typical stress-strain response of TRC under monotonic loading

This study aims to understand better the stiffness degradation and micro-macro cracking mechanism of TRC under uniaxial tensile quasi-cyclic loading. Therefore, a TRC specimen of size $500 \times 60 \times 10$ mm with four layers of AR-glass textile fibers was prepared and tested under uniaxial tensile quasi-cyclic loading. The mechanical test is aided by digital image correlation (DIC) and acoustic emission (AE) techniques. The load-deflection response and stiffness degradation as a function of increasing strain is evaluated. The surface strain distribution and crack formation are obtained using DIC and the evolution of micro-macro cracking in the interior of the specimen is obtained using the AE technique.

2 TRC SPECIMEN PREPRARATION

2.1 Concrete mix

The matrix composition of the concrete mixture consists of Ordinary Portland Cement (OPC), fly ash, and microsilica. A Poly Carboxylate Ether (PCE) superplasticizer is added to the mixture at a rate of 0.15% by weight of the binder. The maximum aggregate size is limited to 1.2 mm to facilitate smooth aggregate penetration through the textile grid. As a result, high-strength concrete with a 28th-day compressive strength of 60 MPa, tensile and flexural strength of 4.5 MPa and 6.9 MPa is produced.

2.2 Textile reinforcement

The mortar matrix contains a leno weave textile reinforcement fabricated from AR-glass roving with a tensile strength of 1650 MPa and a modulus of elasticity of 70 MPa. The textile has a mesh opening size of 16 mm by 16 mm. TRC specimen of dimension $500 \times 60 \times 10$ mm is prepared according to the RILEM TC 232-TDT [15] with 4 layers of AR-glass textile fabric at a 2 mm centre-to-centre distance from each other along the thickness.

3 EXPERIMENTAL PROGRAM

The tensile test on TRC specimens was performed on a servo-controlled electro-mechanical testing machine of capacity 50 kN load cell. The experimental setup and its schematic are shown in Figure 2. The axial displacement along the loading direction is measured using an extensometer mounted along the length of the specimen. Five specimens were initially tested under monotonic loading to obtain the load-deformation curve which showed trilinear response. Further, five specimens were tested under quasi-cyclic loading in displacement control according to the loading pattern as shown in Figure 3. The displacement amplitude of quasi-cyclic loading is decided based on the displacement range corresponding to different zones in the monotonic response. Two cycles at each displacement range were applied. The loading scheme is illustrated in Figure 3. The acoustic emission (AE) and digital image correlation (DIC) techniques are used in conjunction with mechanical testing to understand the fracture and micro-macro cracking mechanisms.

4 Results and discussions

4.1. Typical stress-strain response and stiffness degradation

The result of the stress-strain response under monotonic response is depicted in Figure 4. The typical monotonic response shows three zones

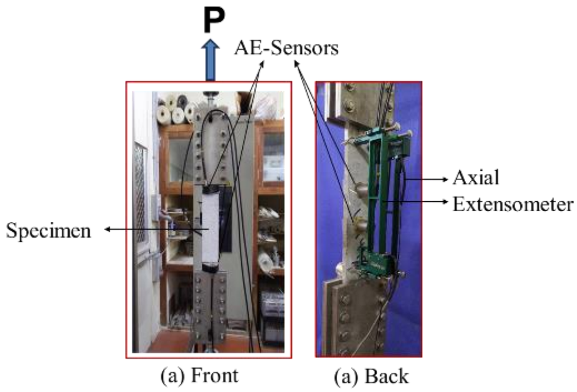

Figure 2. Experimental setup

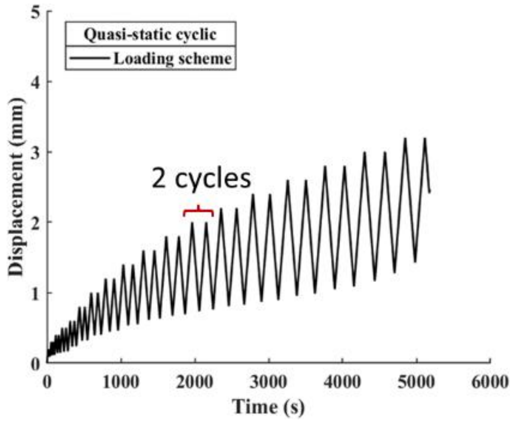

Figure 3. Schematic loading scheme

where zone I is linear attributed to the elastic response of the composite, followed by multiple cracking in zone II and finally in zone III, crack saturation occurs where the load is effectively carried by the textile. The quasi-cyclic response within each of these zones shows a different rate of stiffness degradation. The stiffness is evaluated using the secant modulus which is calculated as the slope of the second loop of the cyclic loading. Figure 5 depicts the plot for the stiffness as a function of strain. In the first zone, at a very low strain (<0.02% strain), stiffness degradation is minimal with a 17% reduction from the initial value. In zone II, the stiffness degrades at a higher rate ranging from 17% to 80% reduction from the initial value. In zone three, the degradation rate is slow ranging between 80% and 95% from the initial value. This analysis gives an idea of how the damage progresses in different zones and will be helpful in damage characterization under fatigue loading which is a part of future work of the authors.

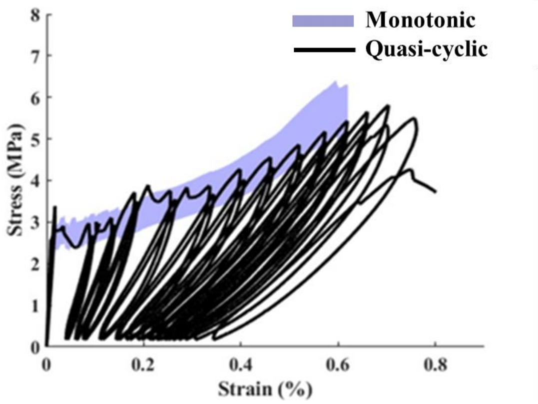

Figure 4. Typical stress-strain response under quasi-cyclic loading

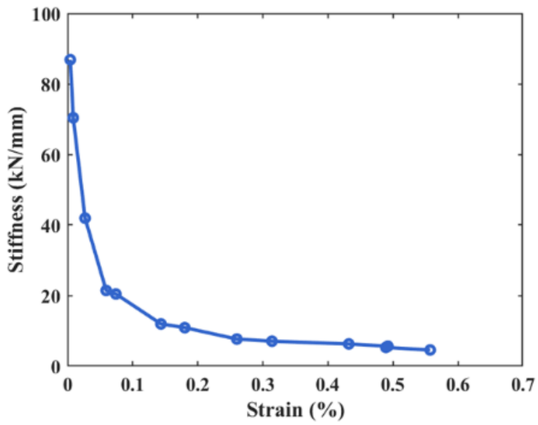

Figure 5. Stiffness degradation as a function of strain

4.2. Fracture characterization from AE and DIC results

The acoustic emission (AE) technique is used to detect the acoustic waves emitted from the microstructural damage such as matrix cracking, debonding, and friction. AE events and energy obtained from the AE technique is an important parameter to characterize the damage progression in the material. In this paper, AE energy is classified into four energy bands (E1 to E4), representing the magnitude of energy evolution. Figure 6 shows the energy evolution, visible strain contour and macro crack formation obtained from AE and DIC results. Figure 6 (c) shows that a significant AE energy evolution occurred before the first crack at a lower strain level of 0.02%. This early-stage AE event activity can be attributed to the initiation and coalescence of micro-cracks in the concrete matrix before the formation of visible macro cracks. As the strain increases AE activity intensifies with an increase in the frequency and high energy AE events (E3 and E4). This corresponds to the multiple cracking phases where cracks propagate in addition to the formation of new ones. By 0.2% strain, 2544 AE events (72% of total AE events) have occurred as shown in Figure 6 (b), and four cracks have already formed indicating the onset of crack saturation. As the strain increases (>0.2% strain), there is a reduction in AE events density, reflecting the transition to a more stable cracking phase. This indicates decreased microstructural activity which aligns with the material entering the strain-hardening phase, where crack propagation dominates over new crack formation. This is evident from the DIC image, where only one additional crack was formed beyond 0.2% strain. Therefore, the AE events recorded in this phase, was mainly due to the interfacial debonding, frictional sliding at the textile-matrix interface and crack widening. This finding indicates the stiffness degradation to be strongly correlated with the matrix micro-macro cracking as the rate of stiffness degradation was substantially high until 0.2% strain, following which the curve flattens.

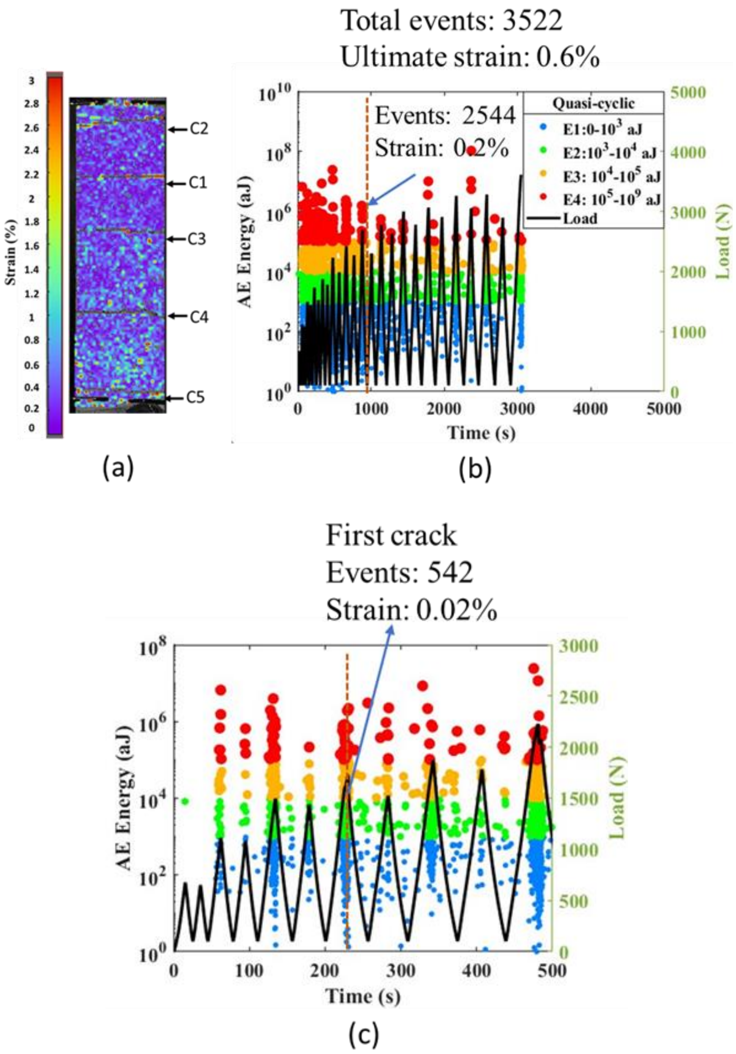

Figure 6. Energy evolution and crack formation of TRC under quasi-cyclic loading obtained from AE and DIC techniques

3.5 Summary and Conclusions

This study investigates the stiffness degradation and fracture behaviour of TRC under quasi-cyclic loading. TRC composites are tested under uniaxial tensile quasi-cyclic loading with the aid of digital image correlation (DIC) and acoustic emission (AE) techniques. The following important conclusions are drawn from this study:

- The analysis of load-deflection responses under quasi-cyclic loading indicates different stages of stiffness deterioration in the investigated TRC composite specimens.
- The initial elastic response (Zone I) exhibits low stiffness reduction of up to 17%, suggesting minimal damage. Zone II exhibits numerous cracks and a significant drop in stiffness, ranging from 17% to 80%, indicating an accelerated deterioration process. Finally, the deterioration rate slows down in Zone III as crack saturation takes place, showing a more stabilized damage state and ranging from 80% to 95% decrease.
- The combined DIC and AE analysis reveals that early stages of loading (<0.2%strain) involve dense and high-frequency AE events activity due to matrix cracking and crack initiation, while at higher strains, AE events reduced in density as cracks stabilized, widened, and propagated.
- The results from the DIC and AE analyses indicate a strong correlation between stiffness degradation and matrix micro-macro cracking of TRC. Further research is needed to explore the relationship between stiffness degradation, AE activity, and crack evolution to gain a deeper understanding of TRC's behaviour under quasi-cyclic loading.

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