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FRACTURE TOUGHNESS OF LATEX-MODIFIED CONCRETE OVERLAYS INTEGRATED WITH MACRO SYNTHETIC FIBERS

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Abstract. *Latex-modified concrete (LMC) overlay demonstrated superior performance as a shielding method for bridge decks. However, cracking glitches and the consequential debonding remain the foremost concern in bridge overlays in general including the LMC overlay. Researchers and practitioners looked for various measures to control this common challenge; and it was proven that the use of synthetic fibers is a commendable solution. Micro synthetic fibers can improve the resistant to shrinkage and temperature cracking, especially at early age, however macro synthetic fibers (MSF) are needed to increase the toughness and residual strength against the repetitive and dynamic loading on bridges. The MSF has low density and only small volumetric fraction is needed to attain the anticipated performance. Majority of investigations in this respect engrossed on the influence of fibers on improving the mechanical characteristics and permanency of concrete. Fairly, limited number of investigational and numerical studies compared the fracture response of fibrous LMC overlays in terms of fracture parameters: energy release rate (G_I) and stress intensity factor (K_I). Hence, this paper assesses the fracture characteristics of LMC overlay entailing applied quantities of MSF with individual formation (length = 40 mm and aspect ratio = 90). Finite element modeling (FEM) was carried out with the aid of ABAQUS to evaluate the fracture characteristics of the LMC with MSF. The FEM modelling and results were adjusted and authenticated based on experimental flexural performance tests carried out according to the ASTM C1609. The results showed that effective fiber content aligned horizontally across the crack path had a significant impact on fracture toughness and residual strength, and relatively small impact on fracture parameters.*

1 INTRODUCTION

Bridge decks require protective topping to minimize the diffusion of the de-icing chlorides; which cause corrosion in the reinforcement systems and wearing complications. The topping mostly referred to as overlay is also wanted to serve as wearing surface and ensure comfortable ridability. Such task requires a concrete overlay with superior performance and endurance; such as the LMC overlays. However, cracking glitches and the consequential debonding remain the foremost concern in bridge overlays in general including the LMC overlay [1-5]. Researchers and practitioners looked for various measures to control this common challenge; and it was proven that the use of synthetic fibers is a commendable solution. The main reasons for debonding and deterioration of the overlay may include: nature of the overlay as a flat area with small thickness, low w/c ratio, severe exposure condition in terms of repetitive loading and impact, application of salt during the freezing season, and condition of the underlying deck. Such effects inflict a precarious situation in the overlay and at its adhesion interface. For that reason, it is acknowledged that it is necessary to boost the performance of the LMC overlays. Addition of MSF to the ingredients of the LMC mixture leads to desirable toughness and post-cracking tensile strength. The MSF has low density and only small volumetric fraction is needed to attain the anticipated performance. Majority of investigations in this respect engrossed on the influence of fibers on improving the mechanical characteristics and permanency of concrete [6-10]. Fairly, limited number of investigational and numerical studies compared the fracture response of fibrous LMC overlays in terms of fracture parameters: energy release rate (G_I) and stress intensity factor (K_I).

Since the 1950s, linear elastic fracture mechanics (LEFM) has been successfully used in the design of brittle materials such as glass and ceramics. Then non-linear elastic fracture mechanics (NLEFM) was developed for metals to include the hardening effect due to the plastic deformation at the front of the crack tip. Concrete is a cementitious material with quasi brittle fracture behavior. In similar to metals, concrete developed a large enough nonlinear zone at the crack tip which must be considered, but this nonlinear zone resulted in stiffening (hardening) in metals, whereas in the concrete resulted in softening damage. Although, concrete structures were successfully analyzed and designed without the use of fracture mechanics (FM), however, FM has many advantages which can be used in further analysis of concrete behavior. For example, FM parameters (i.e., fracture energy) is widely used in finite element modeling of concrete damage of many structures [11]. Also, FM helps to understand the crack imitation, and propagation in concrete up to failure. Furthermore, FM can be used to justify the strength-based size effect of the concrete structure, and further improve the fracture toughness of high strength concrete [12]. Therefore, research on FM of concrete has continued for the last four decades.

2 Experimental Results

The LMC mix designs are shown in Table 1 per cubic meter for all ingredients. The maximum aggregate size is 12.5 mm and the S.G. for both aggregates types is 2.65. The used w/c ratio was 0.37 (50% of the latex is water), which is typically used for producing high performance concrete. No air-entraining or superplasticizer is used in the LMC mix since the latex serves as plasticizing agent and provides inherent flexibility. The target slump for the LMC mixtures is in the range of 7.5 to 15 cm measured after 5 minutes from discharge. The unit weight if the LMC measured in the fresh state was 2304 kg/m^3. The intent from adding MSF to LMC overlay mix is to mitigate cracking and make it tough with residual strength. But, addition of MSF must not harm the slump and ability to finish the LMC overlay. Consequently, the MSF type and amount must be selected carefully to achieve the required performance characteristics without adverse effects. Typically, when the MSF content exceeds 1.8 kg/m^3 in the thin concrete overlays, special attention is required to maintain the target slump and to prevent any finishing problems such as clumping. Consequently, the total fiber content within each overlay mix was limited to 1.8 kg/m^3. Macro fiber type (SX) was selected for the present work. The fiber is 40 mm long blend of polypropylene and polyethylene macro type fiber with S.G. = 0.92, aspect ratio of 90, elastic modulus = 9.5 GPa, and tensile strength = 620 MPa. The present work was part of comprehensive research on fibrous concrete overlays.

Table 1 Proportions of the overlay mix designs

Ingredient	Quantity
Type I cement	395 kg/m^3
Fine aggregate	835 kg/m^3
Coarse aggregate	835 kg/m^3
Styrene butadiene latex	123 L/m^3
w/cm	0.37

The flexural performance test was administered for the LMC mixture with MSF following the ASTM C1609 protocol. The specimens' dimensions were 150x150x540 mm and the loading was displacement-controlled at an amount of 0.06 0.12 mm/min till finishing the test. Fig. 1 shows the machine used for conducting the tests along with the assembly of the specimen. The results showed that the average modulus of rupture of the LMC with MSF was 4.9 MPa with approximately 11% residual strength (0.54 MPa).

Fig. 1. Flexural performance test setup according to ASTM C1609

3 Finite Element Modeling

Researches on fiber-reinforced concrete showed that only fibers that cross the crack path are effective at resisting crack initiation and propagation. In experimental testing of prisms under 3PBT and 4PBT, it is impractical to arrange the individual fibers inside the concrete at the expected location of the crack. Therefore, fibers are mixed with concrete, and then the assumption of uniform distribution of fibers would be equal in the prism. Then the fracture parameters of the concrete prism with and without fibers are determined using formulas and procedures as explained earlier. However, the mechanics and behavior of individual fibers in resisting an active crack can be studied using a numerical model. The FEM provides the perfect solution for assessing the contribution of only effective fibers to the fracture behaver of a concrete prism, where the number, spacing, and orientation can be changed, and their effect can be directly measured. In present work, two basic nonlinear finite element models (NFEM) were developed to further understand the effect of macro fibres on concrete fracture behaviour. In the first part, the effect of fiber content on flexural toughness of concrete was studied: NFEM was developed for the prism without initial notch and the concrete damage plasticity (CDP) model was used to model the nonlinear behaviour of the concrete. In the second part, the effect of different parameters (f'_c, crack length, fiber content) on fracture parameters (G_I, K_I) were investigated. The concrete was modelled as linear elastic, and then the contour integral method implemented in ABAQUS software were used to calculated the fracture parameters.

The 3D eight-node brick element with reduced integration (C3D8R) element was used for concrete modelling. The concrete damage plasticity (CDP) model implemented in ABAQUS was utilized to simulate the behaviour of concrete. In this model, concrete element can fail in compression crushing or tensile cracking. The 2-node linear 3-D truss element (T3D2) was used for fiber modelling. The fibers were modelled as linear elastic with modulus of elasticity of 9500 MPa up to the ultimate strength (620 MPa). The Poisson's ratio was assumed to be 0.30. The interaction between fibers and concrete was embedded region in concrete host element. The fibers were aligned perpendicular to the predefined crack at the mid span of the beam. The spacing and number of fibers were calculated based on the fibers content on the concrete prism.

4. FEM Results

In the first part of this study, a validation of the proposed NLFEM of the solid control prism with fiber content = 1.8 kg/m^3 is performed using the experimental results presented in the Section 2. The simplified solid prism with the effective SX-fibers is illustrated in Fig. 2. Therefore, material properties, loading and support conditions were considered same as the experimental tested prism. The experimental results of load-mid span displacement curve were used in the validation of the NLFEM.

Four models were implemented, one without fibers and the others with (0.0088%, 0.027% and 0.066%) percentage of fibers aligned horizontally. The load displacement curve of the specimen with 0.0088% fibers matches the experimental one with 1.8 kg/m^3 fiber content randomly distributed. This response indicates that only sixteen fibers were effectively aligned perfectly horizontally and arrest the crack propagation as shown in Fig. 3. This figure also reveals that the residual part increased with the increase in the fiber content. The increased residual part reaches 4.14, 8.9 and 15.13 kN at fiber contents of 0.0088%, 0.027% and 0.066%; respectively. This increase is due to the bridging effect provided by the fibers which try to prevent the crack opening.

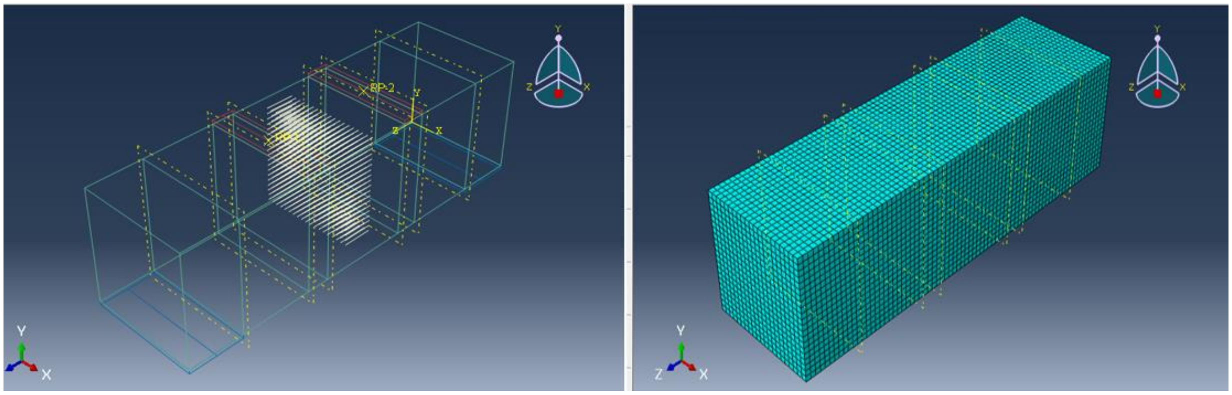

Fig. 2. Finite Element Modeling of Concrete Prism with SX Fibers.

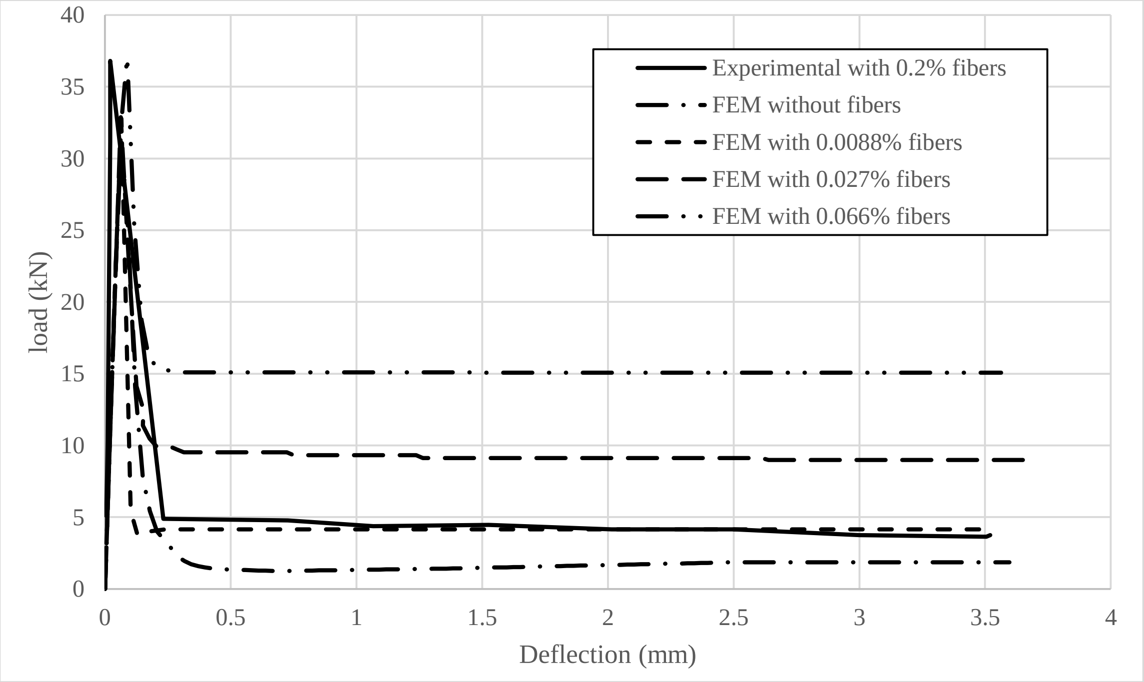

Fig. 3. Comparison between the Load-Displacement Curves for the Experimental and FEM Results.

From the load-deflection curves above, the flexural toughness is computed as the area under the curve divided by the cross-section. It is obvious from the results shown in Table 2 below that the flexural toughness for the specimen with 0.0088% fiber content was 0.706 N/mm compared with 0.83 N/mm for the experimental specimen (14.9% difference). This is because the fibers in the finite element model were aligned horizontally compared with the experimental specimen with random distribution. The results also reveal that the flexural toughness increased with the increase in the fiber content to reach 2.45 N/mm at 0.066% fiber content. This is due to the fibers role in slowing the crack propagation and increasing the area under the load deflection curve.

Table 2: Summary of Fracture Toughness of Concrete Prisms

Specimen Description	Residual load capacity (kN)	Toughness (N/mm)	Normalized Toughness
Experimental with 0.2% random distribution of fibers	3.64	0.83	2.15
FEM without fibers (control)	0	0.386	1
FEM with 16 fibers aligned horizontally (0.0088%)	4.14	0.706	1.83
FEM with 50 fibers aligned horizontally (0.027%)	8.9	1.573	4.08
FEM with 120 fibers aligned horizontally (0.066%)	15.13	2.45	6.35

After proper validation, a parametric study was designed to investigate the effect of fibers content. The NFEM models (Fig. 4) used in the parametric study were same as the developed validated models except that initial crack of size *a* was included. The contour integral method developed was implemented in ABAQUS and used to calculate K_I. The quadratic elements with quarter-point location was assumed for mid side nodes at the crack tip and the concrete mesh size was further refined around the crack tip as a requirement for accurate prediction of fracture stress intensity factor (K_I). Fig. 5 shows a typical stress distribution around the crack tip generated from the FEA.

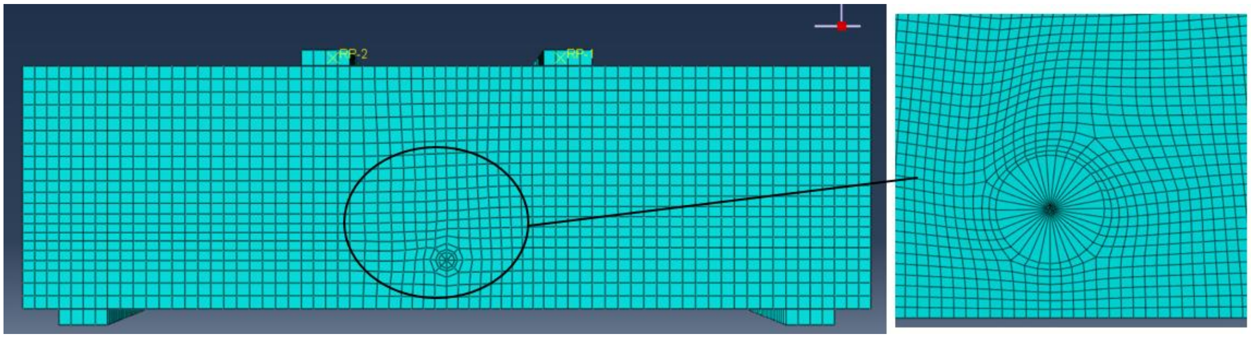

Fig. 4. Finite Element Modeling of Concrete Prism with Initial Crack Size.

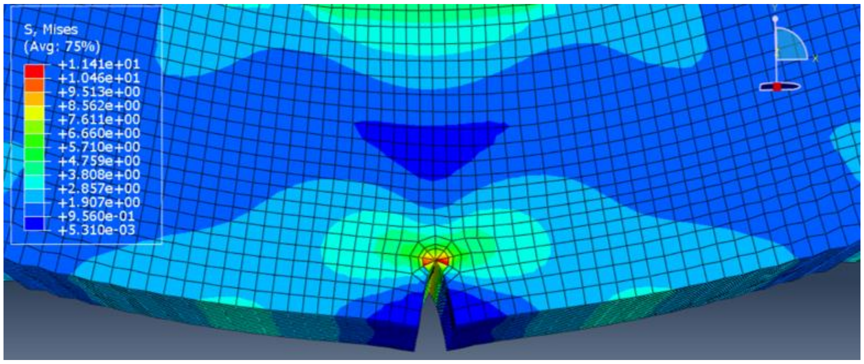

Fig. 5. Typical stress distribution around the crack tip.

The effect of fiber content on the fracture parameters was studied using fiber content varies between 0 and 0.2% of concrete volume. The models had the same concrete compressive strength ($f'c$ = 40 MPa), loading, and initial crack length of 30 mm. As shown in Table 3, the FEM and analytical results was agreed strongly, indicating that FEM model can accurately predict the fracture parameter of prism. Furthermore, Fig. 6 shows that increasing the fiber content relatively decreased both K_I & G_I.

Table 5: FEM Results of K_I and G_I for Different for Different fiber content

Fiber Content (%)	K_I (MPa*mm$^{0.5}$)		G_I (10^{-3}) (N/mm)	
	Analytical	*FEM*	*Analytical*	*FEM*
0	41.74	41.40	58.62	55.34
0.01	41.74	41.36	58.62	55.24
0.02	41.74	41.32	58.62	55.14
0.04	41.74	41.28	58.62	55.04
0.1	41.74	41.03	58.62	54.36
0.2	41.74	40.62	58.62	53.27

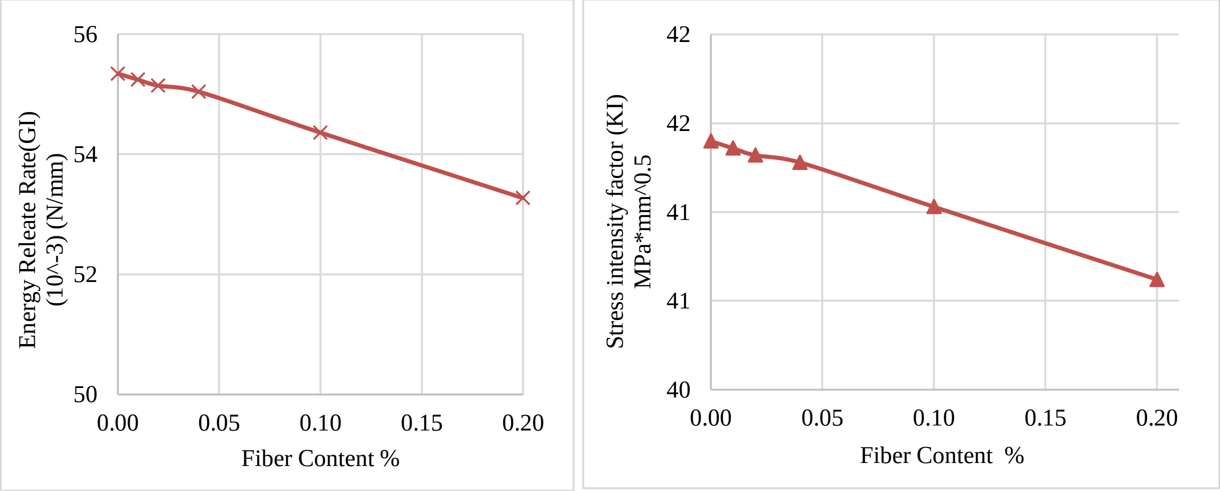

Fig. 6. Analytical and FEM of Fracture Parameters for Different Fiber Content.

5 Conclusion

The effect of SX-fibers on the fracture behaviour of concrete was investigated in the present study. The concrete prism and standard single edge notch bend specimen were used to study the flexural toughness and fracture parameters (G_I, K_I); respectively. Based on the results, it was concluded that the flexural toughness and residual strength were significantly improved with effective horizontal fibers crossing the crack rather than the total fiber content. The flexural toughness of the concrete prisms with 356 fibers randomly distributed within the concrete mixture was approximately equivalent to prisms with 16 fibers uniformly aligned horizontally (perpendicular the crack). Increasing the number of the effective fiber content from 0 to 120 (0.066%), increased the flexural toughness by about 6.4 times. The fiber content had relatively slight impact on the fracture energy release rate and stress intensity factor.

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