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Investigation of crack propagation behavior of impact-resistant functionally graded concrete

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ABSTRACT: This paper conducted research on numerical studies of fracture mechanics related to crack propagation of projectile impact-resistant functionally graded concrete consisting of plain, fiber reinforced and tough aggregate concrete layers, which are presented by modeling a three-point bending test in presence of initial notch. To consider fracture behavior in process zone, a bilinear softening model for plain and tough aggregate concrete and a trilinear softening model obtained from traction-separation relationship of cohesive zone model is used. Extended finite element method is utilized for numerical analysis. result of numerical modeling of three-point bending test have been investigated and compared using loading versus crack mouth opening displacement (P-CMOD) curves. Functionally graded model has been studied in comparison with homogeneous plain, fiber reinforced and tough aggregate concrete models, and the results showed that homogeneous fiber reinforced concrete model has a better fracture behavior than others models. The functionally graded model has not been subjected to sudden failure in comparison with plain and tough aggregate concrete models due to the fiber reinforced in end layer. Also, effect of each layer and their thickness change in the functionally graded model are evaluated and it was observed that fiber reinforced layer due to high fracture energy created by fiber bridging has a beneficial effect on the fracture behavior related to other layers. In this way, by considering proper position and thickness for this layer, in addition to providing appropriate performance in the fracture behavior, cost of materials also be significantly reduced.

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1. INTRODUCTION

With the increasing of terrorist attacks, the need for research to develop protective and economic structures is more and more necessary that are able to withstand extreme loads such as explosion waves and projectile impact. With the development of technology and materials, new forms of protection for structures can be obtained. A structure should generally provide safety, serviceability, optimum economic conditions and operational capability. Functionally graded cementitious materials (FGM) is a new concept for cement mortar technology to reduce costs and improve the mechanical performance of these materials along with other benefits.

Since concrete cracks cannot be avoided, therefore, in order to study concrete behavior in the presence of cracks, the use of fracture mechanics criteria is a necessity. The fracture mechanics investigates the behavior of materials in the presence of cracks and defects like them, and provides an appropriate tool for measuring the fracture resistance or durability of materials [1]. The behavior of most materials in fracture mechanics results from the behavior of materials in the fracture process zone [2]. Tensile fracture behavior of concrete-based materials can be expressed by curves of tensile strength against crack opening width (cohesive zone models). The traction applied to the crack surfaces in the cohesive zone models decreases with increasing crack opening and does not suddenly drop to zero. In general, traction-separation relationships of cohesive zone models can be classified into potential-based models and non-potential-based models [3]. Potential-based models use the concept of cohesive energy potential [4]. For non-potential-based models, traction-separation models have been developed with different shapes, for example, linear softening [5], trapezoidal shape [6], bilinear softening [7, 8], trilinear softening [9] and exponential models [10, 11].

In this research, an impact-resistant functionally graded concrete has been selected according to previous studies, and its fracture behavior has been investigated and its proper performance has been thoroughly described. In fact, the main objective of this study is to achieve the crack growth pattern in the FG concrete by three-point bending test model in the presence of the initial crack. For this purpose, the three-dimensional finite element program (ABAQUS) has been granted. In this study, using a suitable behavior of concrete

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Table 1. mechanical and fracture parameters.

Material	E (Gpa)	υ	f'_t (Mpa)	G_f (N.m/m^2)	G_F or G_{FRC} (N.m/m^2)	CTODc (mm)
PC	27.2	0.2	3.44	38.3	120	0.016
FRC	26.5	0.2	4.22	37.1	3531	0.016

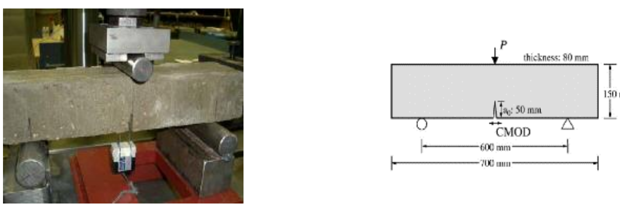

Fig. 1. The geometry of the beam in the three-point bending test [9].

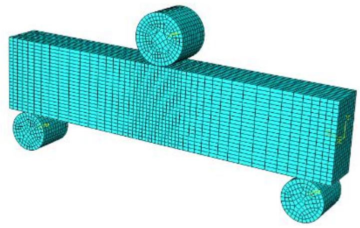

Fig. 2. Software model of three-point bending test.

fracture mechanics by validating with existing research, the modeling pattern has been chosen to simulate the three-point bending test in three-dimensions without any simplification in materials and geometry.

2. METHODOLOGY AND VERIFICATION

In this research, the extended finite element method (XFEM) has been used to analyze crack growth. Roesler et al.'s paper [9] have been used to validate the crack growth behavior in ABAQUS software. In aforementioned paper, the fracture parameters are obtained by using a three-point bending test, and the bilinear and trilinear traction-separation relationships are presented for plain concrete (PC) and fiber reinforced concrete (FRC) for growth cracking, respectively. The traction-separation relationship in ABAQUS was initially developed by Camanho et al. [11].

In this paper, verification has been carried out for concrete specimens using traction-separation relationships for crack growth in the fracture process zone and numerical modeling of three-point bending test for plain and fiber reinforced concrete and the results are presented by load versus crack mouth opening displacement (P-CMOD). The mechanical and fracture parameters [9] including elastic modulus (E), Poisson's ratio (υ), tensile strength (f'_t), initial fracture energy (G_f), total fracture energy of plain concrete (G_F), total fracture energy of FRC (G_{FRC}) and critical crack opening displacement ($CTOD_c$) are summarized in Table 1. In fiber reinforced concrete, steel fiber is used and its length is 40 mm. The geometry of the beam in the three-point bending test of Roesler et al. [9] is shown in Figure 1.

The three-point bending test modeling is similar to the test specimens. The software model is shown in Figure 2. The modeling of the beam and the supports in the software is defined as the 8-node hexahedron solid element. The initial crack is a shell element and is introduced as a XFEM crack. The boundary conditions in the center of the rigid cylinders shown in Figure 2 are considered to be fixed completely and the contact between the cylinders with the concrete beam is frictionally. Controlled loading is applied to the center of the beam via the intermediate cylinder.

In ABAQUS software, the maximum stress criterion for crack growth has been used and the displacement criterion (crack opening) has been used to develop the crack growth. In order to develop the crack growth, the bilinear and trilinear traction-separation relationships have been applied to plain concrete and fiber reinforced concrete by tabular softening in ABAQUS software, respectively. The verification results of finite element simulations for PC and FRC are presented in Figures 3 and 4 in comparison with the numerical and test results of Roesler et al. [9] by load versus crack mouth opening displacement (P-CMOD) curves.

3. RESULTS AND DISCUSSION

The functionally graded materials not only provide appropriate performance for the structure, but also reduce costs. In this research, with the aim of providing protection considerations, a geometric pattern of projectile impact-resistant is selected for cementitious functionally graded materials from previous studies. In the present paper, the proposed projectile impact-resistant geometry for the cementitious functionally graded materials by Quek et al. [12] is considered, and the behavior of its fracture mechanism was studied by modeling of the three-point bending test in the presence of the initial crack. The geometric pattern for the FG-cementitious panels as FG-1:1:7:1 that was proposed by Quek and et al. [12] has been selected as a standard specimen in this study. Each FG-cementitious panel is named using a set of corresponding numbers as ten percent of the overall thickness of panel for each layer. For instance, the first number "2" in "FG-2:1:6:1" means that the first layer is 30 mm thick for a panel with overall thickness of 150 mm. Various cementitious specimens that have been used to investigate the behavior of fracture mechanics are summarized in Table 2. The mechanical and fracture parameters for the three concrete material of

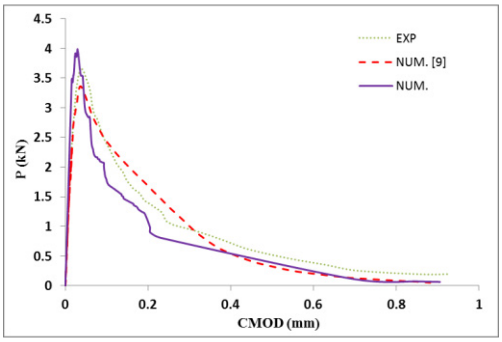

Fig. 3. Comparison between FE results and numerical and test results of Roesler et al. [9] for PC specimens.

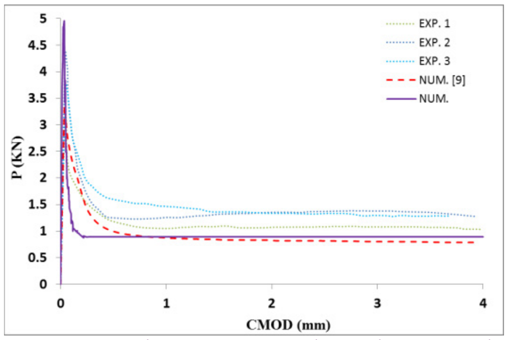

Fig. 4. Comparison between FE results and numerical and test results of Roesler et al. [9] for FRC specimens.

Table 2. Summary of studied cementitious specimens.

Specimen designation	Remarks	
Plain	Plain concrete	
FRC	Fiber reinforced concrete	
Tough agg.	Tough aggregate concrete	
FG-1:1:7:1	Standard FG-cementitious	
FG-2:1:6:1	Increased impact face FRC layer thickness	
FG-1:2:6:1	Increased tough aggregate concrete layer thickness	
FG-1:1:1:6:1	Add a layer of FRC beneath the tough concrete layer	

Table 3. mechanical and fracture parameters.

material	E (Gpa)	υ	f'_t (Mpa)	G_f (N.m/m^2)	G_F or G_{FRC} (N.m/m^2)	CTODc (mm)
PC	32.72	0.2	2.46	40	120	0.02
FRC	19.83	0.2	2.58	40	2100	0.02
Tough agg.	40.42	0.2	3.19	40	160	0.02

plain concrete, fiber reinforced concrete and tough aggregate concrete are assumed as Table 3.

The geometric dimensions of the three-point bending test model in this case are similar to Figure 1. The initial crack is located in the distal face of impact and its length is 50 mm.

3.1. Efficiency of standard FG-cementitious

In this section, standard FG-cementitious specimen has been compared with full depth specimens of plain concrete, fiber reinforced concrete and tough aggregate concrete. The P-CMOD curves for these four specimens in the modeling of

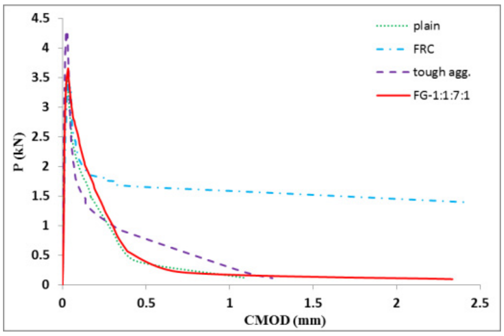

Fig. 5. Comparison between FE results for standard FG-cementitious specimen compared with full depth specimens of PC, FRC and Tough agg..

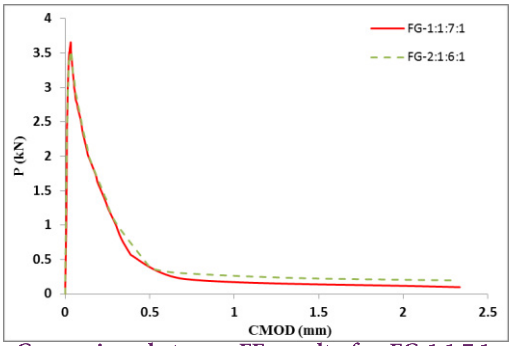

Fig. 6. Comparison between FE results for FG-1:1:7:1 and FG-2:1:6:1.

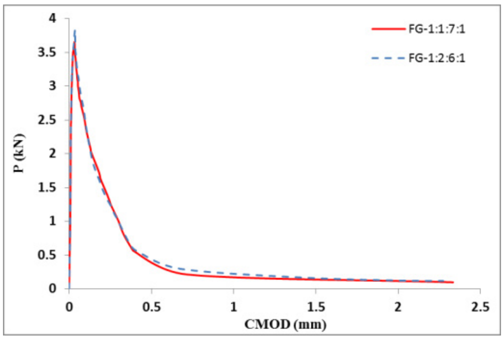

Fig. 7. comparison between FE results for FG-1:1:7:1 and FG-1:2:6:1.

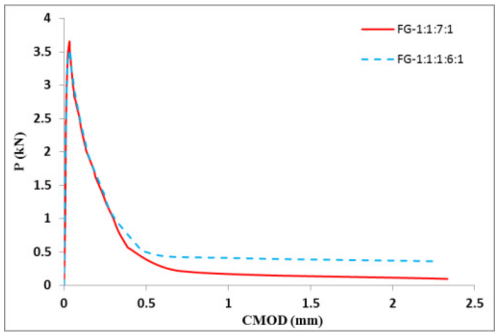

Fig. 8. Comparison between FE results for FG-1:1:7:1 and FG-1:1:1:6:1.

the three-point bending test is shown in Figure 5. The peak load is higher in the tough aggregate concrete, which is due to the high tensile strength of this type of concrete (Table 3) compared to other specimens. Since the end of the initial crack of the functionally graded specimen is in the plain concrete layer, the behavior of this specimen to the peak load is similar to that of the plain concrete. For post-peak load behavior, the fiber reinforced concrete has a much better performance than other specimens, which results from high fracture energy due to the fibers bridging. This fibers bridging is the required fracture energy to pull out the fibers from the concrete during the crack opening. As shown in Figure 5, FRC layer of functionally graded specimen prevents the sudden failure of the panel compared to homogeneous plain and tough aggregate concrete.

3.2. Effects of increased impact face FRC layer thickness

In this section, the effect of FRC layer by doubling its thickness has been studied. This functionally graded specimen is named FG-2:1:6:1 and compared with the FG-1:1:7:1 by the P-CMOD curves (Figure 6). Since the tip of the initial crack in these two specimens is in the plain concrete layer, the behavior to the peak load is the same in both specimens. At the beginning of the post-peak load, two curves coincide, but the end portion of the softening curve in FG-2:1:6:1 is higher than FG-1:1:7:1 due to the high thickness of the fiber reinforced concrete layer. In the crack tip opening of 1.5 mm, the load in the two specimens of FG-1:1:7:1 and FG-1:1:6:1 is 0.16 kN and 0.21 kN, respectively. Therefore, with doubling the thickness of the impact face FRC layer in the case study specimens, the required load for crack tip opening of 1.5 mm has increased by about 30%.

3.3. Effects of Increased tough aggregate concrete layer thickness

In this section, FG-1:1:7:1 and FG-1:2:6:1 specimens were compared by modeling of three-point bending test. In Figure 7, the P-CMOD curves is illustrated for two specimens. The P-CMOD curve for the two specimens corresponds approximately to each other, which has been expected due to the application of this layer in the functionally graded panel.

3.4. Effects of Add a layer of FRC beneath the tough aggregate concrete layer

According to the results obtained in the previous sections, the FRC layer has a very positive effect on the fracture behavior of the concrete. For this reason, a FRC layer with a thickness of 15 mm has been added between plain concrete and tough aggregate concrete layers in the functionally graded specimen and its fracture behavior has been compared with the standard FG-cementitious specimen. The comparison of two FG-1:1:7:1 and FG-1:1:1:6:1 specimens is also shown in Fig. 8 by the P-CMOD curve. As shown in Figure 8, before the peak load and in the sharp slope of post-peak load, two curves are similar due to the same characteristics of the materials. While the FG-1:1:1:6:1 shows a much better performance than the FG-1:1:7:1 at the low slope of the post-peak load.

The load at the crack tip opening of 1.5 mm in the sample FG-1:1:1:6:1 is 0.4 kN, which is increased by about 60% compared with the FG-1:1:7:1 specimen. Also, the FG-1:1:1:6:1 shows better performance than the FG-2:1:6:1 with the same volume of materials.

4. CONCLUSIONS

In this paper, a suitable geometric model for impact-resistant cementitious functionally graded materials was selected and its fracture behavior was evaluated using a numerical model of the three-point bending test and compared with homogeneous concrete specimens. Finally, the effect of each of its layers on the fracture behavior was investigated. The results were obtained using the curves of load versus crack mouth opening displacement (P-CMOD). The results of this research are as follow: (1) In the P-CMOD is derived from the numerical modeling of the three-point bending test, the peak load is dependent on the tensile strength of the concrete material in which the crack tip is located. (2) Unlike plain concrete and tough aggregate concrete specimens, FG-cementitious specimens did not fail suddenly due to the presence of fiber reinforced concrete layer at the end face. (3) The fracture behavior of the fiber reinforced concrete specimen was considerably better than other specimens, but the use of this specimen imposes a high cost. (4) By doubling the thickness of the FRC layer in the loading face, the performance of FG-cementitious specimen improved, so that for the crack tip opening of 1.5 mm in the three-point bending test, the required load increased by about 30%. (5) increasing the thickness of the tough aggregate concrete layer has slight effect on the fracture behavior of the FG-cementitious specimen due to low difference in its fracture energy compared to plain concrete. (6) By adding a FRC layer between plain concrete and tough aggregate concrete layers in the functionally graded specimen, the fracture behavior was significantly improved, so that for the crack tip opening of 1.5 mm in the three-point bending test, the required load increased by about 60% compared to the standard FG-cementitious specimen.

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