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AGGREGATE MULTI-INCLUSION INTERACTION AND INTERFACE INFLUENCE ON CONCRETE COMPRESSION BEHAVIOR

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The presence of the interfacial transition zone (ITZ) between aggregates and the mortar matrix in concrete has been studied extensively. A numerical and experimental study involving concrete specimens with multi-inclusions was conducted, and the ITZ was modeled as a cutoff bar in the finite element analysis, representing the shear and tensile behavior. The mortar specimens were sized 100 mm by 100 mm, with a thickness of 50 mm, and the inclusions were cylindrical aggregates with a diameter of 20.85 mm. The specimen was loaded in uniaxial compression. Two inclusion axes configurations were considered: parallel and perpendicular to the line of loading. The finite element analysis was performed assuming a 2D behavior. Further, the aspect of the distance between inclusions was studied. It was shown that, in general, the perpendicular arrangement resulted in a significantly higher compression strength when compared to the parallel formation. For both the parallel and perpendicular configuration, the relationship between the increase in the axis distance and the compression strength followed a quadratic path. First an increase in strength was observed, followed by a reduction, as the axis distance evolved. Additionally, it was shown that the ITZ area in tension initiated the failure of all specimens.

Keywords: Inclusions configuration, Axis distance, Compression strength.

1 INTRODUCTION

Studies have been conducted on the behavior of mortar specimens with single inclusions, incorporating the interfacial transition zone (ITZ). To analyze the influence of this ITZ to the compression strength, a finite element model (FEM) was constructed representing the ITZ as a cutoff bar (Setiawan 2014). The tension and shear load-displacement responses of this ITZ were obtained experimentally (Han and Sabdono 2011), and further functioned as input to the model. The study demonstrated that the larger the inclusion diameter-to-specimen area ratio, the lower the uniaxial compression strength of the specimens (Han *et al.* 2015). Experimental studies on specimens with multi-inclusions showed that an increase in inclusion number influenced the strength negatively (Suarjana 1998, Darwin 1999). In addition, the fracture analysis on multi-inclusion specimens concluded that the fracture energy at which the specimen fails depended on the size of the mortar strip between the aggregates (Alzebdeh *et al.* 1998, Kan *et al.* 2004). A study on the effect of aggregate expansion to the mortar damage was conducted more recently, suggesting that not only the size of the mortar, but also the bond between the mortar and the aggregate state, plays a role in the failure behavior of the mortar (Pour-Ghaz and Weiss 2010).

Han *et al.* (2013) experimentally found that the distance between the axis of the inclusions and the configuration of aggregates with respect to the line of load had a major impact on the load-carrying capacity. In general, the inclusions arranged parallel to the line of load SV3 and SV4 had a lower compression strength, compared to SH3 and SH4 having their inclusions arranged perpendicularly to the load direction. However, an increase in the axis distance from 30 mm to 40 mm resulted in a strength enhancement for both SV and SH. See Figure 1. The experimental results also showed that for the SH specimens, four columnar cracks demarcated the failure of the element, in comparison to the SV type that had only two major crack propagations. The CL data originated from the single-inclusion specimen.

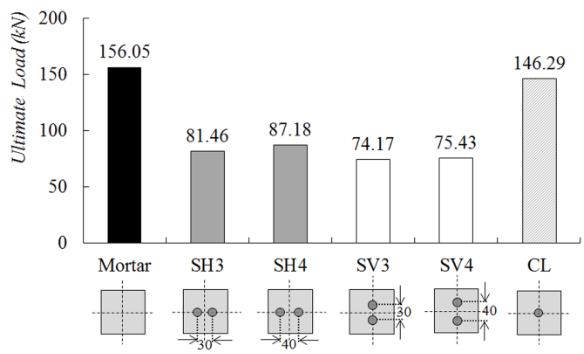


Figure 1. Compression strength comparison.

These intriguing findings lead to the study on the influence of the aggregate inclusions configuration and their relative axes distances. For finite element analysis (FEA) purposes, the cutoff bar was introduced into the multi-inclusion model. The FEA was performed using Strand7 software. To ensure that the proposed model, originally developed for a single inclusion aggregate, was valid, the load-displacement curves obtained experimentally were compared to the FEA output. The ultimate load, as well as the stiffness behavior under an incremental load, was studied. As proven to be accurate, the model was utilized to run for a variation in inclusion-axes distances.

2 EXPERIMENTAL STUDY

The experimental study provided the material and ITZ properties as input to the FEM, and the specimen load-displacement responses for the FEM validation purposes.

2.1 Material Property Data

Since the concrete was considered as a three-phase, rather than two-phase, material, the properties that were sought for were the shear and tensile behavior of the ITZ, and the uniaxial compression strength f'_c and the Poisson's ratio υ of the mortar and the aggregate. The stress-strain constitutive relationship and the Young's modulus of the mortar were approached by the *fib* Model Code for Concrete (2010). Mortar has an approximately similar mechanical behavior to concrete (Harsh *et al.* 1990, Daczko 1999). The testing methods for concrete behavior were hence expected to be applicable to mortar. The cylindrical specimens were sized 100 mm by 200 mm; as for the aggregates, cored cylinders sized 20.80 mm by 40 mm were tested. The mortar had a compression strength of 32.6 MPa, with a Young's modulus of 31.9 GPa and a Poisson's ratio of 0.22. The aggregate had a strength of 159 MPa, an elastic modulus of 74.7 GPa with a Poisson's ratio of 0.25.

2.2 ITZ behavior

The cutoff bar used in this model required the ITZ behavior in tension and shear. These data were obtained experimentally, assuming an independent behavior (Han and Sabdono 2011). The response in tension was quadratic, but in this study approached linearly by the secant stiffness method. The response in shear was bilinear, as a contribution from the bond and adhesion in the material. Only the first branch of the curve was accessed since the ITZ is characterized by bond failure. The properties of this ITZ were a function of the element area, depending on the fineness of the meshing. The stiffness in tension was 0.67 N/mm/mm^2 and an ultimate load of 0.47 N/mm^2. The stiffness in shear was 0.37 N/mm with an ultimate load of 5.64 N/mm^2.

2.3 Validation specimens

The proposed cutoff bar model was proven very suitable for representing single inclusion specimens (Han *et al.* 2015). However, applying the model to multi-inclusion required re-evaluation. A number of numerical improvements were introduced, including the use of the arc-length iteration technique. To ensure the compatibility of the FEM for multi-inclusion, laboratory tested specimens were casted having the exact same mortar and aggregate material properties. The validation specimens were sized 100 mm by 100 mm with a thickness of 50 mm. Two 20.80 mm cylindrical inclusions were placed horizontally, each having an axis distance of 40 mm. The specimens were tested in uniaxial compression, and the load-displacement responses recorded.

3 THE FINITE ELEMENT MODEL

The FEA algorithms distinguished the material behavior in three ways: the mortar approached nonlinearly, taking into account the failure boundaries; the aggregates had a linear response; and the ITZ behaved linearly and was limited by the ultimate loading in tension and shear. The cutoff bar was designed as a multiple bar-spring element.

3.1 Mortar and aggregates

The mortar matrix was assumed nonlinearly isotropic, and the max-stress failure envelope mandated the failure of a Gauss point. This envelope does not take into account the confinement in biaxial compression, nor does it accommodate the weakening effect of the tension-compression principal stress combination. The aggregate was substantially stronger than the mortar, having a compression strength almost five times the mortar, with a stiffness twice the mortar. Therefore the failure of the aggregates was not considered in the analysis. A constant stiffness modulus was used throughout the analysis.

3.2 The ITZ

In modeling, the ITZ was represented by the cutoff bar element, consisting of three bars and four links (Setiawan 2014), one bar for accommodating the tensile response, and two bars for incorporating the shear-tension and shear-compression mode. The links connected the bars with the nodes in the mortar, and the aggregate. Since the laboratory data were expressed in a normalized form per area, the stiffness and ultimate load were multiplied by the average area between the two elements connecting the cutoff bar. The bar dimensions were further equipped to transform the ITZ stiffness into the elastic modulus of the bars.

4 VALIDATION AND RESULTS

The load-displacement response of the element SH4 resulted by the FEM was validated by the experimental data and shown in Figure 2.

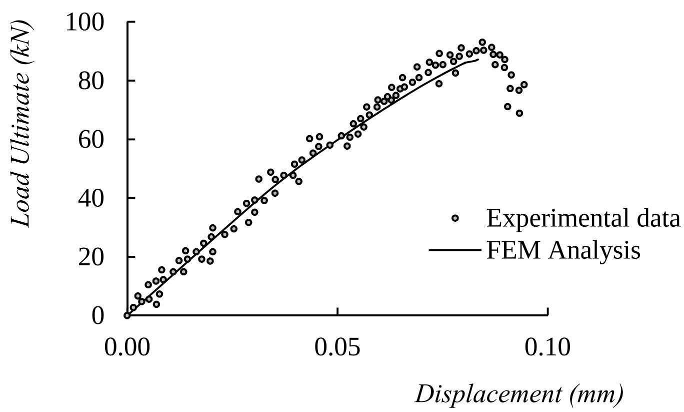


Figure 2. ITZ FEM validation.

The curve comparison showed that the proposed FEM accurately predicted the stiffness response of the specimen under incremental monotonic loading. Upon reaching the ultimate load, the FEM showed a slight instability, a numerical flaw most likely originating from the mesh configuration that required finer meshing in areas subjected to high stresses. The FEM also slightly underestimated the ultimate load at which the specimen failed, and was not able to produce the post-peak behavior that was observed from the experimental data.

The FEM was further utilized to analyze the influence of the inclusion distance to the ultimate loading capacity of the specimen. For this objective, a range of axis distances were numerically created and run through the program. The distances ranged between 30 mm to 70 mm with a graduation of 10 mm. The resulting ultimate loads as predicted by the FEM were plotted against the relative distance of inclusion axis with respect to the specimen width, and shown in Figure 3.

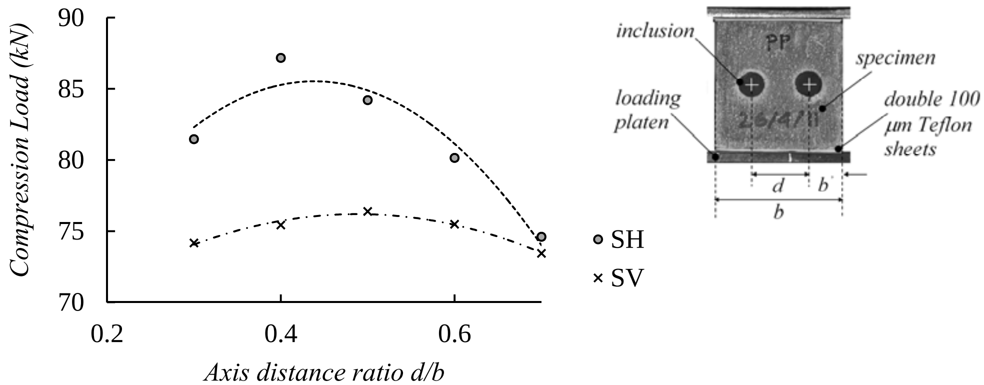
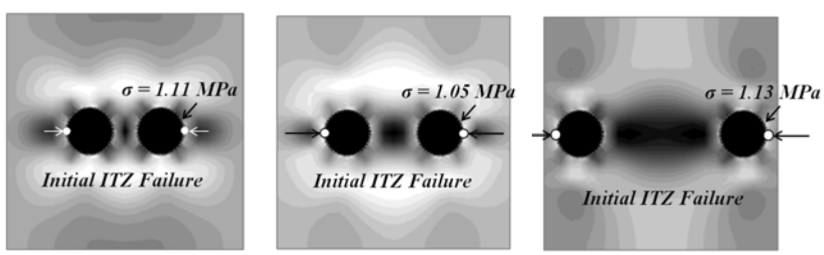


Figure 3. Axes distance response.

To observe the first failure in the ITZ and mortar matrix, the perpendicular model SH3, SH4, and SH7 was run for a small constant load. The stress distributions for the specimens are shown in Figure 4. The dark shadows reflexed the compression stress areas, while the light contours represented the tension stress regions. For all specimens, the ITZ, on the right and left adjacent to the aggregates, initiated the bond failure. The maximum stress in the mortar occurred at the Gauss points in tension-compression. The magnitude of the major tensile stress, at which the first crack in the mortar occurred in SH3, SH4, and SH7, is as shown in Figure 4.



SH3 SH4 SH7

Figure 4. Stress distribution in the mortar.

5 CONCLUSIONS

The FEA showed that an increase in inclusion axis-to-specimen width ratio *d/b* first resulted in an enhancement in compression strength. This could be explained by the fact that stress concentrations along the mortar strip *d* decreased as the space between the inclusions widened. When the axis distance was made longer, the ultimate compression load decreased, and the compression strength continued to drop as a function of an increase in *d/b* ratio. Although the intensity of stresses in the strip between inclusions became lower, the stresses opposite the aggregates in the strip *b'* began to rise simultaneously. It was concluded that the ratio *d/b* equaling 0.4 for SH thus demarcates the optimum balanced stress point in the *d* and *b'* strip of the mortar. The visual study on the stress contours of the specimen underlined this finding, since the major principal tensile stress in the material was the highest for specimen SH7. The parallel arranged inclusions exhibited a similar pattern, except that for a *d/b* ratio of 0.5 the optimum was found.

All the specimens SH and SV initially failed in the ITZ in tension, adjacent to the inclusion. This resulted in the differentiation in cracking pattern between the parallel and perpendicular arranged inclusions. The study concluded that the presence of inclusions significantly influenced the compression strength of the specimen. The stress concentration in the mortar between the inclusions, perpendicular to the line of loading, is critical to the initial cracking of the mortar, and the ultimate failure load of the specimen. The failure always started in the ITZ in tension, and the ITZ first failure was always detected on the outer left and right in the ITZ, adjacent to the aggregate.

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