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# DAMAGED MODEL FOR COUNTERFEIT COHESIVE FRACTURE BEHAVIOR OF MULTI-PHASE HYBRID MATERIALS

**Suman S**[*1]

[*1]Lecturer, Department Of Mechanical Engineering, Vidyavardhaka Polytechnic, Mysuru, Karnataka, India.

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## ABSTRACT

We propose a new damage model for bluffing the cohesive fracture behaviour of multi-phase compound Materials similar as concrete. The proposed model can estimate the damage of the matrix- phase in compound Materials using the volume bit of the matrix within an element comprising the matrix and other Materials .The damage model was first formulated for 1D problems and also extended to two- dimensional (2D) and three-dimensional( 3D) problems using the original strain grounded on the modified von- Mises criterion. The validity of the damage model was indicated for 1D and 2D problems, and the model was also applied to the simulation of 3D cohesive crack growth in a miscellaneous solid with a large number of globular eliminations. The results confirm that the proposed model allows the meshless finite element analysis of cohesive fracturing in compound Materials.

**Keywords:** Damage Model, Multi-Phase Compound, Cohesive Fracture, Concrete, Meshless Analysis.

## I. INTRODUCTION

Concrete is extensively used as a construction material in civil engineering structures, and can be considered as a miscellaneous material comprising a mortar matrix and coarse aggregate eliminations in the meso- scale, which corresponds to centimeter scale. Generally, mortar without summations and concrete with summations parade different fracture behaviors, and thus have different material strength and durability. Concrete has advanced durability than mortar owing to the presence of coarse summations, which complicates the concrete's fracture results in cracks generating and propagating dispersedly at colorful locales within the concrete. This implies that coarse summations play a mechanically significant part in the distortion and fracture behavior of concrete.

In ordinary concrete, cracks infrequently access coarse summations. In numerous cases, cracks propagate within the mortar and around the coarse summations. To reproduce this fracture using numerical analysis, it's necessary to prepare an analysis mesh that reflects the figure and distribution of summations, and to pretend the cohesive crack propagation of mortar. Still, such an analysis mesh for a miscellaneous structure with plenitude of summations is delicate to induce owing to the summations' colorful shapes and arbitrary distribution. Also, indeed if the mesh could be prepared, it would still be delicate to pretend the cohesive crack propagation. The mesh generation for a complicated micro- or meso- structure, and the analysis of crack propagation are both major challenges for computational mechanics and the finite element system (FEM).

Numerical analyses for the crack propagation in the concrete's meso- scale have been conducted, and numerous similar analyses have employed separate models, similar as the separate- element model( 1 – 3), the chassis model( 4 – 8), and the rigid- body- spring model (9 – 11), as analysis tools for bluffing spastic distortion. These approaches allow the simulation of crack propagation and its relations with the coarse summations in concrete because they enable the easy modeling of spastic distortion. Although the chassis or separate modeling fits the simulation of complicated fracture, similar as that of concrete, the top debit of the abovementioned models is that the numerical result is explosively dependent on the mesh pattern and snare size.

## II. METHODOLOGY

The FEM is a reasonable choice as a tool for structural analysis. numerous studies have reported the analysis of the concrete's meso- structure using the FEM, and have achieved the generation of finite element meshes along the figure of coarse summations by replacing the factual summations with simple artificial numbers similar as two- dimensional( 2D) circles or polygons in( 12 – 15), and three- dimensional( 3D) spheres or polyhedrons in(16 – 21). To pretend the fracture of the meso- structure of factual concrete, the problem of mesh generation must first be answered.

Image- grounded analyses have been conducted using the reckoned tomography image of concrete to dissect factual concrete's meso- structures (22 – 26). Utmost of these analyses use the Voxel- type FEM, which allows the direct metamorphosis of the digital image into a finite element mesh (27 – 30). Although the Voxel FEM has the advantage of fluently reflecting the complicated figure of summations using a grid mesh rather of mesh generation in agreement with the figure, the zigzag- patterned mesh reduces the delicacy of stress.

At the material interfaces. Also, the demand of a fine mesh to express a smooth figure increases the computational cost. In recent times, the virtual element system (31) has been applied to dissect concrete's mesostructured reconstructed by-ray and neutron- reckoned tomography images (32). Computational ways for modeling the arbitrary distribution of coarse summations with a complex figure have also been Delved (33 – 35).

As an indispensable approach for avoiding the difficulty of mesh generation, mesh free or meshless analyses similar as the extended FEM( XFEM)( 36), the finite cover system( FCM) ( 37), and other affiliated styles, have been applied to the analysis of miscellaneous solids similar as concrete. These styles can dissect the crack growth and the miscellaneous solids without mesh generation along the physical boundaries (38, 39). Also, meshless analysis is a possible approach toward bluffing the crack growth in the concrete's meso structure, but its operation to the analysis of multiple cracks in miscellaneous solids is delicate, owing to physical boundaries similar as cracks or interfaces, which must be captured and traced during the finite element analysis, rather of entrapping re-meshing along the physical boundaries. The arbitrary crack growth can be expressed using a fine mesh, owing to the system's low dependence on mesh size. The operation of this system to the crack propagation analysis of the mortar phase enables the simulation of the fracture of the concrete's meso-structure, but simulation has not yet been achieved owing to the difficulty of mesh generation, as reported by other studies. Therefore, the first point to be addressed is the development of an approach for bluffing the fracture of miscellaneous solids in a meshless manner.

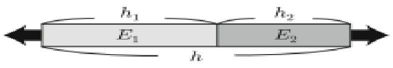
## III. MODELING AND ANALYSIS

### Expression of damage model

This section presents the expression of the proposed damage model for bluffing the cohesive fracture of multi-phase compound Materials. First, the damage model is formulated as a 1D problem grounded on the elastic result of a compound bar problem. Also, the 1D expression is extended to multi-dimensional problems u sings the original strain and stress. The characteristics of meshless finite element analysis formulation phase compound Materials using the damage model is also described.

### Expression in 1D problem

The pressure problem of the two- phase compound bar shown in Fig. 1 is set to formulate the damage model, wherein the compound bar doesn't include the interface. This section targets the compound bar in which different Materials are arranged in series under tensile cargo to model the tensile damage of multi-phase compound Materials.



(a) Elastic state without damage

(b) Damaged state

**Fig. 1.** Tensile problem of an elastic bar comprising two materials: an elastic state without damage; b damaged state

N numerous cases of multi-phase mixes, the stress re-division due to fracture damages the only weakest material. Therefore, the damage is assumed to be convinced only in Material 1. Let h1 and E1 be the length and Young's modulus of Material 1, independently, and h2 and E2 be the length and Young's modulus of Material 2, independently. The cross-sectional area is constant throughout the bar. By letting h = h1+ h2 be the total length of the bar, the volume bit of Materials 1 and 2 can be expressed as follows

$$V = \frac{h_1}{h}; \quad 1 - V = \frac{h_2}{h}$$

Where V is the volume fraction of Material 1.

First, let us consider the elastic state without damage, as shown in Fig. 1 a. The axial force is constant in the composite bar, wherein different materials are arranged in series. With a constant cross-section, the stress is also constant throughout the bar and can be expressed as follows:

$$\sigma = E_1\varepsilon_1 = E_2\varepsilon_2$$

Where ε1 and ε2 are the strain of Materials 1 and 2, respectively. From the relationship between the displacement and strain, the average strain of the entire bar can be calculated using the volume fraction of the materials in above equation, as follows:

$$\varepsilon = \frac{\varepsilon_1 h_1 + \varepsilon_2 h_2}{h} = V_1\varepsilon_1 + (1 - V)\varepsilon_2$$

Substituting the value of ε in the stress equation we get the relationship between stress and strain as

$$\sigma = \left(\frac{V}{E_1} + \frac{1 - V}{E_2}\right)^{-1} \varepsilon = E\varepsilon$$

Where E is the average Young's modulus for the composite bar, and is expressed as follows:

$$E = \left(\frac{V}{E_1} + \frac{1 - V}{E_2}\right)^{-1}$$

To model the cohesive fracture process inquasi-brittle Materials , a fracture mechanics model grounded on the energy balance approach in terms of fracture energy, as proposed by Hillerborg et al.( 42), is introduced into the damage model. Specifically, the following relationship between the cohesive- traction force and the crack-opening relegation on the crack faces, which has the same form as in( 43) and as shown in Fig. 2, is used as the fracture mechanics model, as follows:

$$t_1 = \bar{t}_1 \exp\left(-\frac{\bar{t}_1}{G_f} w_1\right)$$

where t1 is the cohesive-traction force per unit area,w1 is the crack-opening displacement, t ¯ 1 is the fracture (damage) initiation stress, Gf is the fracture energy, and subsript 1 indicates Material 1. Again, note that fracture (damage) initiation is allowed only in Material 1. For 1D problems, the cohesive-traction force accommodates the stress as follows:

$$t_1 = \sigma_1; \quad \bar{t}_1 = \bar{\sigma}_1 = E_1\bar{\varepsilon}_1$$

where σ1 and ¯σ1 are the stress and the fracture (damage) initiation stress of Material 1, respectively. From the relationship between displacement and strain, the crack-opening displacement of Material 1, w1 can be calculated as follows:

$$w_1 = \varepsilon_1 h_1 - \bar{\varepsilon}_1 h_1 = (\varepsilon_1 - \bar{\varepsilon}_1)h_1$$

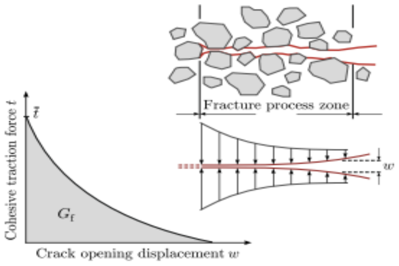


**Fig. 2.** Relationship between cohesive-traction force and crack-opening displacement in fracture process zone of quasi-brittle materials

## IV. RESULTS AND DISCUSSION

### Verification of damage model

The proposed damage model enables the damage evaluation of the matrix- phase in composite Materials within the frame of meshless finite element analysis. This section presents several numerical exemplifications to corroborate the validity of the damage model and demonstrate the vacuity of meshless finite element analysis.

### Verification illustration in 1D

Fig. 3. compares the cargo–relegation responses attained by the reference analysis and the proposed analysis. The vertical axis indicates the apparent strain calculated as the relegation divided by the length of the model, while the perpendicular axis represents the apparent stress defined as the cargo divided by the lading area. The results verified that the proposed model has good fit to the reference result and allows the damage evaluation of Material 1 within the element by only using the volume bit. This indicates the validity of the damage model grounded on the elastic result of a 1D compound bar problem.

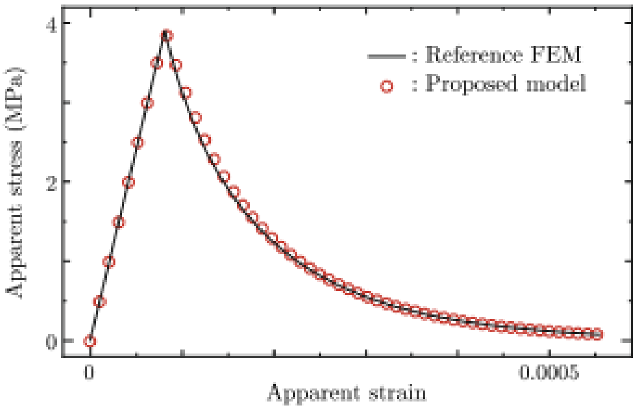
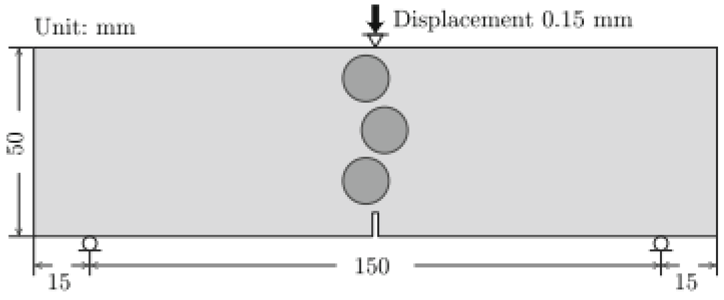


**Fig. 3.** Comparison of load–displacement curves in 1D bar problem



| | $E$ GPa | $\nu$ | $\bar{\varepsilon}$ | $G_f$ N/mm | $k$ |
|---|---|---|---|---|---|
| Matrix | 20 | 0.2 | 0.0002 | 0.05 | 10 |
| Inclusions | 60 | 0.2 | — | — | — |

**Fig. 4.** Three-point bending problem of beam with three circular inclusions

### Verification illustration in 2D

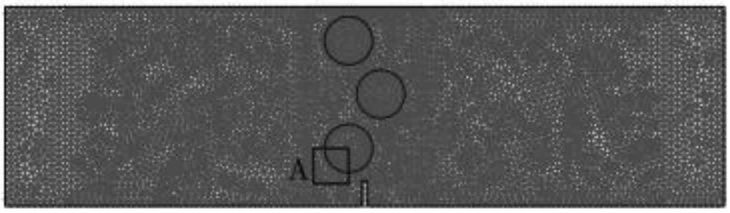
Next, the validity of the proposed damage model was vindicated for 2D problems. Unlike 1D problems, the damage may be estimated by using the equivalent strain. The main difference from 1D problems is that the original strain is used in finite element analysis with the damage model. The analysis target is a ray with a single- edge notch subordinated to three- point bending under the aero plane strain condition, as shown in Fig. 4. To probe the crack propagation, the ray has three indirect eliminations in the region where the crack propagates. The material parameters of the matrix and the eliminations are presented in Fig. 4, and it's assumed that the eliminations don't fracture.

Fig. 5. shows two finite element mesh types. The mesh sizes are determined similar that the addition shapes can be sufficiently reproduced. The finite element meshes in Fig. 5a. was generated according to the material interfaces, and used for reference analysis. Fig. 5b. presents the finite element mesh for applying the proposed damage model; the mesh was generated irrespectively of the material interfaces. The difference of the morass is egregious, as can be seen from the enlarged view shown in Fig. 5c.

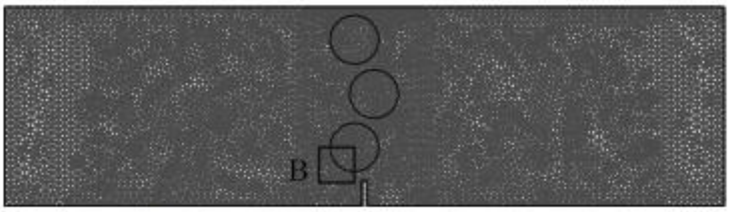
Fig. 6 compares the cargo – relegation angles attained from the reference analysis and proposed analysis. The response attained from the proposed model is in good agreement with the reference result. This means that, in the same manner as for 2D problems, the proposed damage model is able of assessing the damage of the matrix- phase in compound Materials using the volume bit of the matrix within the element.

The distributions of original strain are shown in Fig. 7. The damage in the proposed model is estimated grounded on the original strain, and the strain localization in such an analysis with a damage model can be considered as cracking. therefore, it becomes possible to fantasize the crack propagation by displaying the original strain distribution, which takes the damage inauguration strain as the minimal value, as shown in Fig. 7.

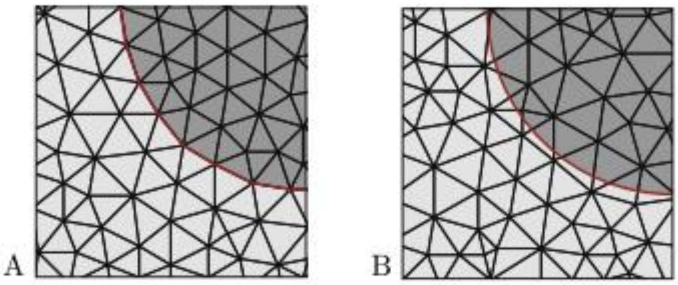
For convenience, the strain localization caused by damage is appertained to as " crack " in this paper. The comparison of these results revealed that the path and rate of crack propagation are roughly the same, and therefore the proposed model is able of assessing only the matrix- phase damage within rudiments arranged irrespectively of the material interfaces. The damage model formulated in this paper can also gain satisfactory results for 2D problems.



(a) Finite element mesh for reference analysis



(b) Finite element mesh for proposed analysis



(c) Closeup of each mesh

**Fig. 5.** Finite element meshes for 2D three-point bending problem

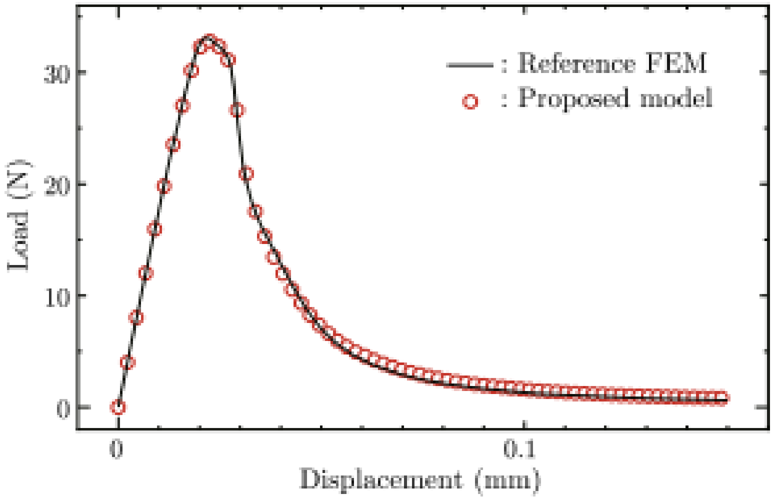
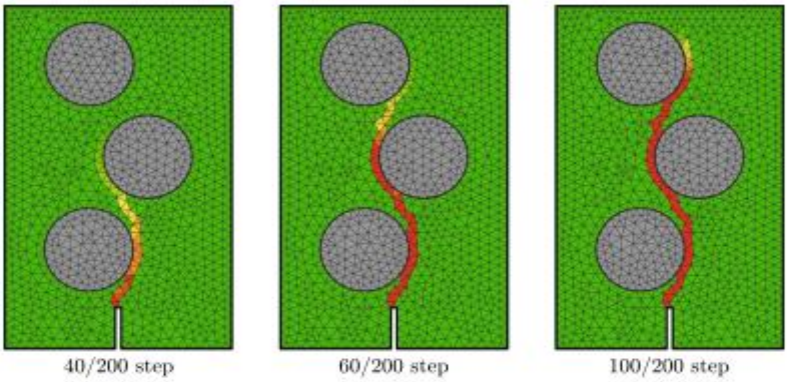
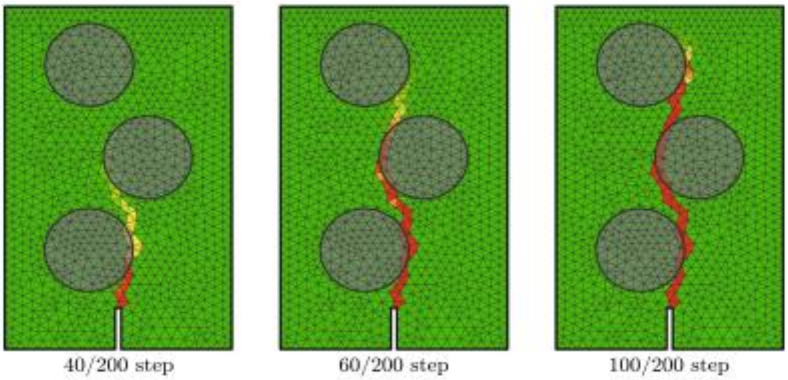


**Fig. 6.** Comparison of load–displacement curves in 2D beam problem



**(a)** Equivalent strain distribution obtained by the reference analysis



**(b)** Equivalent strain distribution obtained by the proposed model

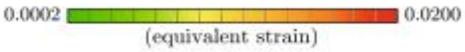


**Fig. 7.** Comparison of damage propagation: left figures show the reference solutions; right figures present the results obtained by the proposed model

## V. CONCLUSION

This paper presented a new damage model for bluffing the cohesive fracture of multi-phase compound Materials . An outstanding point of the proposed model is its capability of assessing the matrix- phase damage within an element comprising different Materials, which therefore enables the meshless finite element analysis of crack growth in compound Materials . This is attributed to the expression of the damage model on the base of a theoretical result of 1D elastic compound bar problems.

Several numerical exemplifications were presented to demonstrate the validity and vacuity of the proposed model. The validity of the expression grounded on the elastic result of compound bar problems was first vindicated for a 1D problem. also, a 2D problem was answered to corroborate the capability of assessing the damage of the matrix- phase in compound Materials . The numerical result also revealed that the proposed model allows the meshless finite element analysis of crack propagation in multi-phase compound Materials using the volume bit of the matrix within the element, rather of generating a finite element mesh in agreement with the material interfaces. Eventually, the proposed model was applied to the simulation of 3D cohesive crack growth in a miscellaneous solid with a large number of globular eliminations, and the attained results demonstrated that the proposed damage model can potentially pretend the cohesive fracture of the meso-structure of factual concrete.

For simplicity, our results are limited to the analysis of two- phase miscellaneous materials with indirect or globular eliminations without interfaces. still, owing to its meshless nature, the proposed model is also applicable to the analysis of real compound Materials with arbitrarily- shaped eliminations, similar as concrete. To this end, unborn work should formulate the interfacial damage between the matrix and eliminations and demonstrate that the damage model facilitates the analysis of cohesive crack growth in the micro- or meso- structure of factual compound Materials . either, the damage model should also be examined for its connection to fracture problems subordinated to other lading patterns.

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