MESOSCALE MODELLING OF CONCRETE SUBJECTED TO BALLISTIC IMPACT

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ABSTRACT

Concrete is a multiphase material commonly used in protective structures and critical infrastructure, consisting primarily of a cement matrix, aggregates and an interfacial transition zone (ITZ). The properties of the aggregates – such as volume fraction, size and shape – play a critical role in determining the overall performance and protective capabilities of such concrete structures. Modifying these aggregate properties offers the ability for enhancing the protective capacity of concrete. Given the extensive research and numerical modelling efforts on concrete subjected to various loading conditions using homogeneous models, it is worth exploring mesoscale modelling approaches where the cement matrix and aggregates are modelled separately. By doing so, we may uncover optimized configurations or designs that provide superior protective solutions. In this paper we look at three themes: (1) An aggregate placing procedure to get sufficiently high-volume fractions in the concrete and the proceeding meshing. High volume fractions are commonly difficult to obtain using create-and-drop methods, so we have implemented an aggregate compacting workflow; (2) Finite element simulations in LS-DYNA of compression tests on cubes and cylinders, and comparison to relevant experiment data; (3) Numerical simulations of ballistic impact tests to investigate the influence of aggregate properties on the ballistic perforation resistance. With information available at the design stage, we create realistic two-phase heterogeneous meshes for finite element simulations in LS-DYNA and compare the results to a homogeneous mesh and literature data. We show that some of the scatter commonly seen in concrete experiments can be attributed to variation in aggregate placement when the cumulative volume fraction remains constant. The results are promising, the models are efficient, and the modelling workflow is streamlined.

Keywords: mesoscale modelling, ballistic impact, numerical simulations, material heterogeneity.

1 INTRODUCTION

Concrete is a material frequently used in protective structures and critical infrastructure due to its versatility, availability, low price and high strength. The material is therefore constantly subject to threats of accidental or intended impact loads, such as blast or ballistic impact. A great amount of research effort has been put into numerical modelling of concrete exposed to such loads, where the material is often assumed to be homogenous [1]. On a component level, the assumption of homogeneity can give decent and accurate results, but for more localised problems like ballistic impacts, scatter in the structural behaviour cannot be effectively characterised without a heterogeneous model with a randomised aggregate structure.

In recent years, mesoscale modelling approaches have been studied frequently used in finite element simulations of concrete to study heterogeneity [1], [2]. Two of the main challenges in mesoscale modelling is compatibility between aggregate creation and meshing, as well as reaching realistically high aggregate volume fractions with reasonable computational effort. In this study, we present a simulation framework to build realistic heterogeneous meshes of a concrete material that can be used for material tests simulations and on component level simulations of ballistic perforation of concrete slabs. We compare

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the results from three realistic, heterogeneous, two-phase meshes to a homogeneous mesh with concrete materials parameters and compare the results to experiment data from the open literature [3].

2 AGGREGATE CREATION AND PLACEMENT PROCEDURE

The following aggregate placement procedure has been developed to reach high aggregate volume fractions in the concrete. The aggregate placement procedure is divided in four steps: (1) creating aggregates based on material information available in the design stage, such as volume fraction and particle size distribution; (2) place aggregates inside a prismatic volume using Python; (3) compact those aggregates in a finite element simulation; (4) loop over a background mesh to see if the element centre is inside an aggregate. If so, the element is flagged as an aggregate element and assigned an aggregate material formulation.

2.1 Aggregate creation

The aggregate creation is performed in Python and follows a frequently used principle: define a sphere with a diameter D_p around a centre point, and sample i vertices on the sphere, encompassing the centre point. This sampling method produces a convex polyhedron that can be triangulated. Each triangular face (with three vertices) can be connected to the centre point to create a tetrahedron element that can be written to a mesh-file for FE analysis. By looping over the elements in a separate background FE mesh, we can check if each element centre of the regular background mesh is inside the aggregate polyhedron and assign aggregate material properties if it is. The procedure is shown in Fig. 1.

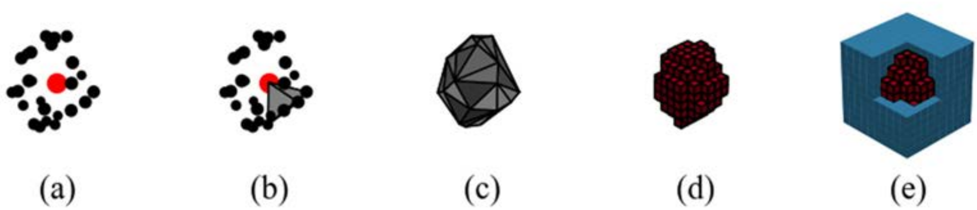

Figure 1: Aggregate creation and meshing shown for one aggregate. (a) i = 25 vertices (black) sampled on a sphere surround the red centre point; (b) Grouping three vertices to the centre point to create a tetrahedron; (c) All tetrahedrons that make up one aggregate; (d) Transferring the Python aggregate to a finite element mesh; and (e) The aggregate mesh in a surrounding matrix mesh.

2.2 Aggregate compacting procedure

Previous studies on mesoscale modelling on concrete have shown that it is difficult to reach aggregate volume fractions above 30% with create-and-place methods. Liang and Zou [4] developed a method where the aggregates were created in a volume with a larger height than the final volume that should be meshed. Then, the aggregates were compacted into the final volume in an FE simulation. The results from the FE analysis can be read by e.g., Python, and by looping over a background mesh, a final mesh can be created based on the final aggregates. The compaction procedure is shown in Fig. 2 and happens between (c) and (d) in Fig. 1.

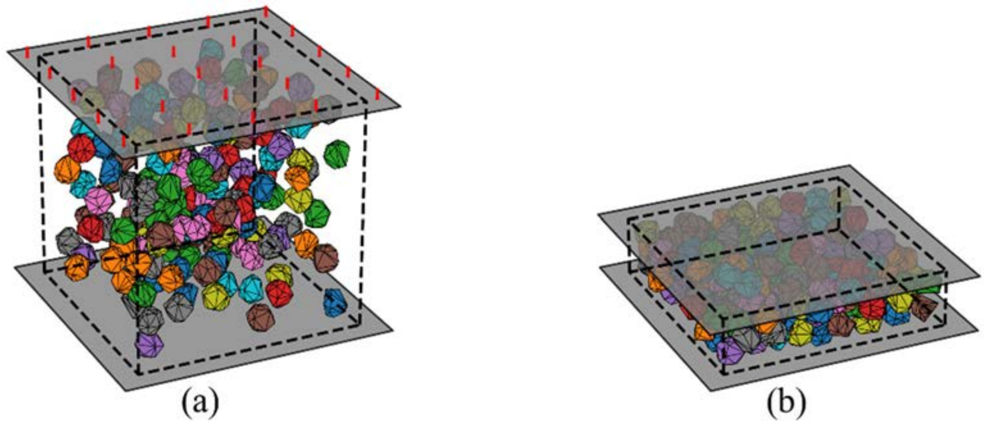

Figure 2: Aggregate compacting. (a) Aggregates in the initial state; and (b) Aggregates compacted into the final volume.

3 MATERIAL MODEL AND MATERIAL PARAMETERS

We used a modified version of the Holmquist–Johnson–Cook concrete (denoted MHJC) model for both the matrix and the aggregates in the numerical simulations of ballistic impact, and for the homogeneous concrete slab. The material model has previously been coined a good compromise between accuracy and ease-of-calibration [5] and has produced decent results in previous papers [3], [6]. The pressure-dependent deviatoric response in the model is described by eqn (1):

$$\sigma_{\mathrm{eq}}^{*}=\frac{\sigma_{\mathrm{eq}}}{f_{\mathrm{c}}}=\begin{cases}B(P^{*}+T^{*}(1-D))^{N}F\left(\dot{\varepsilon}_{\mathrm{eq}}^{*}\right)R(\theta,e) & \text{for } P^{*}\geq -T^{*}(1-D)\\ 0 & \text{for } P^{*}<-T^{*}(1-D)\end{cases},\qquad (1)$$

where σ_{eq}^{*} is the equivalent stress normalised with respect to the unconfined compressive strength f_{c}. B and N are pressure-hardening parameters, P^{*} and T^{*} are the hydrostatic pressure and maximum tensile hydrostatic pressure, both normalised with respect to f_{c}. D is a damage variable that accounts for both compaction and shear damage, while $F\left(\dot{\varepsilon}_{\mathrm{eq}}^{*}\right)$ is a rate-dependent two-parameter term with the strain-rate sensitivity parameter C. Finally, $R(\theta,e)$ further accounts for triaxial stress states with the Lode angle θ. The model also describes and accounts for the equation-of-state through a three-part formulation. P_{lock} is part of the equation-of-state and is the hydrostatic pressure at which all the air voids in the concrete are crushed.

Material parameters in the following simulations were not directly calibrated from material tests but found using literature data and reasonable assumptions. The main idea is to have high-strength aggregates and a lower-strength matrix material. When simulating two concretes with different strengths, only the material parameters for the matrix material would have to change. Three sets of material parameters have to be found for the simulations in this study: one set of parameters for the concrete material in the homogeneous mesh – and one set of parameters for each of the matrix and aggregates in the heterogeneous meshes. The main material parameters are listed in Table 1.

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The numerical simulations of ballistic impact herein are a proof-of-concept rather than precise recreations of the experiment results.

Table 1: Main material parameters of the MHJC model used in the simulations.

Parameter	Homogeneous model	Heterogeneous model	
	Concrete	Matrix	Aggregate
ρ (kg/m^3)	2,400	2,000	2,700
f_c (MPa)	75	70	160
B (−)	1.7	1.8	1.6
N (−)	0.7	0.7	0.7
T (MPa)	4.0	4.0	4.0
C (−)	0.02	0.02	0.02
P_{lock} (MPa)	800	400	800

4.1 Setup of the ballistic model

For the simulations, we used the base information from Kristoffersen et al. [3] and their C75 50 mm thick concrete slabs to set it up. The slab was modelled as a 400 × 400 × 50 mm prism part. The elements were modelled as 8-node solids, with side length 2 mm and 1 integration point, as well as a viscous hourglass control. The outer edges of the slab were fixed for all translations. The ogival projectile was modelled as a rigid material with mass 196 g and contact was defined as node-to-surface (projectile nodes). We set up two cases for the slab – one homogeneous slab modelled with a concrete material model, and one where the matrix and aggregates were modelled separately, but both with the MHJC material model. Three heterogeneous meshes were created with the same initial conditions, but different aggregate structure. The concrete in the experiments had a volume fraction of coarse aggregates (8–16 mm) of roughly 30%, so the same volume fraction is used for the heterogeneous meshes.

Fig. 3 shows how the aggregates were distributed in one of the heterogeneous meshes. Aggregates have only been compacted into the middle prism of the slabs with size 200 × 200 × 50 mm, as the projectile will not affect elements outside this zone.

4.2 Results from the numerical modelling

All simulations had projectile initial velocity v_{i} of $250\ \mathrm{m/s}$. The projectile residual velocities v_{r} were found and compared to an experiment with approximately the same initial velocity. Fig. 4 shows the final state from the simulations when the projectiles have completely perforated the slabs. The projectiles in the simulations with heterogeneous meshes are rotated post perforation, and the three scabbing areas differ in shape. Both the homogeneous and heterogeneous meshes resulted in lower residual velocities compared to the experiments.

While both approaches yield reasonable results, the heterogeneous models offer the advantage of capturing scatter, allowing for a more detailed investigation. Both meshes produced scabbing areas on the backside that resembled the experiment in a qualitative manner. However, the numerical models were not able to capture any of the dust that occurred in the experiments. This is likely due to the element size – an element size of 2 mm cannot capture this effect when element erosion is used.

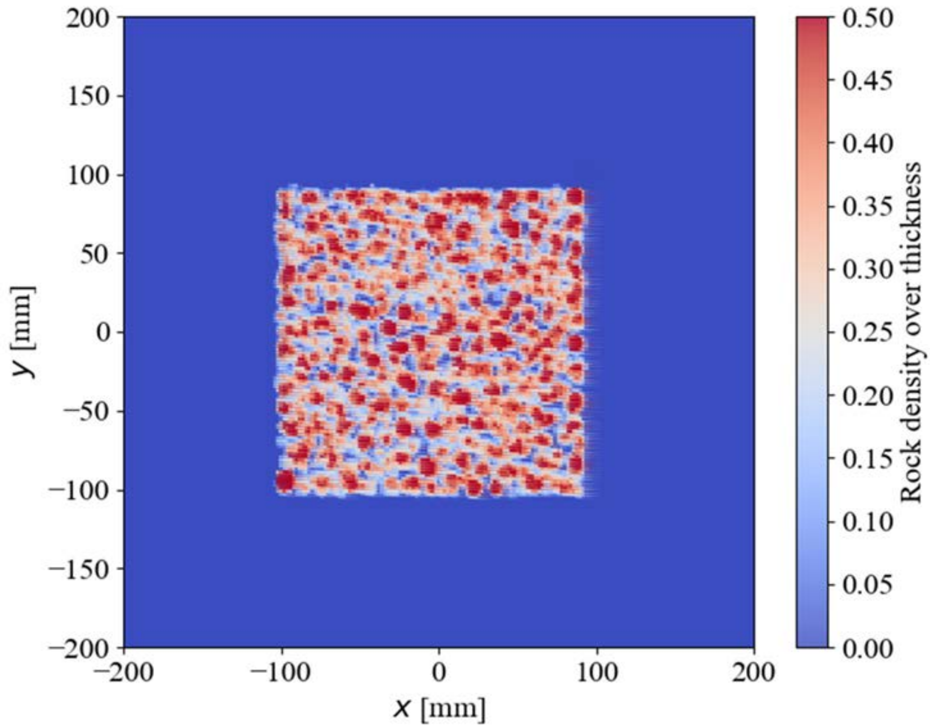

Figure 3: The heterogeneous mesh used in one of the three mesoscale simulations. Only a middle prism is modelled with aggregates, the rest of the slab is only matrix material. The projectile impacted the slab in $(x, y, z) = (0, 0, 50)$.

Table 2: Projectile velocities from experiment, homogeneous mesh and heterogeneous meshes.

Parameter	**Experiment [3]**	**Homogeneous mesh**	**Heterogeneous mesh**		
			No. 1	**No. 2**	**No. 3**
v_i (m/s)	253.4	250.0	250.0	250.0	250.0
v_r (m/s)	170.3	147.2	141.6	136.6	142.3

5 CONCLUSIONS AND OUTLOOK

We set up a workflow to create realistic, heterogeneous meshes of concrete material meshes using data that usually is available at the design stage. Numerical simulations of ballistic experiments served as proof-of-concept of the method, with relevant comparisons to a homogeneous mesh.

The mesoscale modelling approach can be used to simulate material tests to investigate scatter seen in experimental testing. Extensive testing would be necessary for characterisation of the matrix and aggregate material to provide accurate predictions of concrete material behaviour. The method could in principle be used on any available load case that is usually modelled using homogeneous concrete models, which would provide further details into the structural behaviour of concrete under ballistic impact.

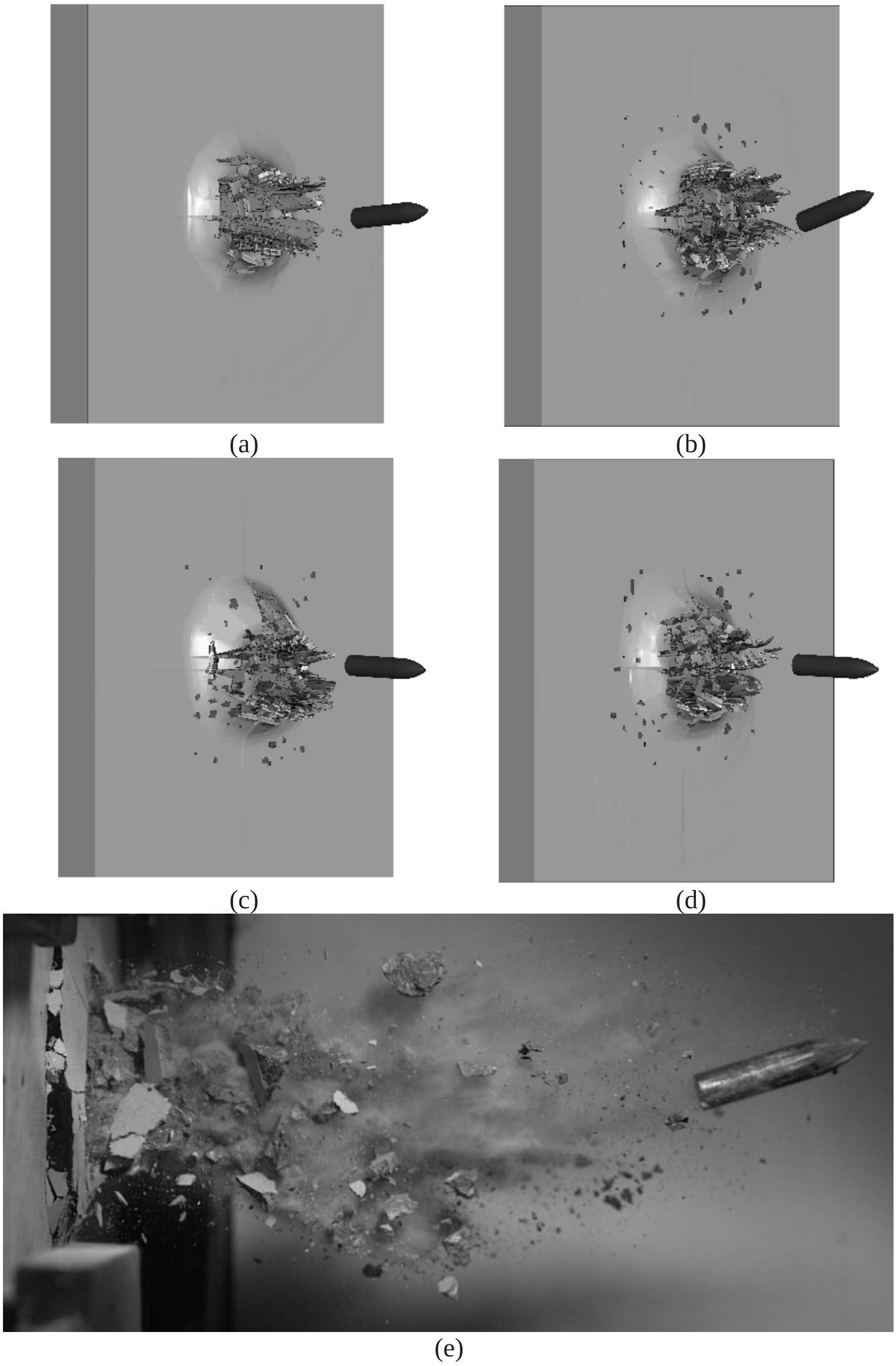

Figure 4: Pictures of the final state for (a) a homogeneous mesh; and (b), (c), (d) three heterogeneous meshes; (e) shows the projectile after perforation of the slab from a concurrent experiment [3].

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