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# FRACTURE SIMULATION OF CONCRETE WITH ASR AND DEF EXPANSIONS BY RBSM

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**Abstract:** In this study, cracking behaviors affected by two main expansion causes: Alkali-silica reaction (ASR) and Delayed ettringite formation (DEF), are predicted by the three-dimensional Rigid Body Spring Model (RBSM). By dissection concrete into 2~3mm randomized polynomial elements and analysis the forces between elements through spring connecting them, RBSM is especially a good solution for fracture analyses. For DEF, initial expansion strain is applied between mortar elements, to reflect the expansion caused by high temperature during curing, which is more concentrated in the inner part where mortar elements experienced higher curing temperature. While in the case of ASR, the expansion strain is applied at the mortar-aggregate interfaces, to reflect the alkali-silica gel formation in and around the aggregates. This is an effective approach to discuss the effect of these two common causes of concrete expansion in long-term, which is difficult to be analyzed using traditional experiment due to its long experiment term required and complexity of quantitatively determinate the contribution of each expansion cause.

In this simulation, cracking patterns due to ASR and DEF are well presented. Especially in ASR case, cracks are more localized with expansion given more concentrated. In DEF case, localized crack is well simulated when the expansion is intensified in the center considering the high-temperature zone during the curing.

## 1 INTRODUCTION

Concrete structures do suffer from many kinds of deteriorations. Among them, Alkali-silica reaction (ASR) and Delayed Ettringite Formation (DEF) are two very common and important expansion processes [1-4]. However, with a similar surface cracking pattern, it is difficult to identify and analyze the expansion reasons and their contribution to mechanical properties losses separately [3-5]. Besides, experimentations may require several years for the cracking to develop in the laboratory [6-7].

Hence, numerical simulation at mesoscale here can be a beneficial tool in understanding the internal stress and internal crack condition due to different expansion reasons. In this study, the three-dimensional Rigid Body Spring Model (3D RBSM) is introduced for this purpose. Mortar is modified using 3D elements in with size around 2 mm, and the sphere shape of aggregates also modeled directly. It has been confirmed by our research group [8-9] that the 3D RBSM is a proper solution in quantitatively evaluate the concrete behavior and mechanical properties.

The objective of this research is to investigate the concrete cracking behavior under expansion due to ASR and DEF using numerical simulation.

## 2 METHOD OF NUMERICAL ANALYSIS

In this study, 3D RBSM is introduced in simulation, which is proposed by Kawai et al. [10]. A three-dimensional concrete model is formed from rigid body meshes.

To prevent cracking propagation in arbitrary directions, here Voronoi diagram is introduced in meshing, as the propagation of cracks in concrete is one of the most important factors affecting the behavior of concrete.

As illustrated in Fig.1, to represent concrete, two types of elements are used, which are the aggregate elements and the mortar elements.

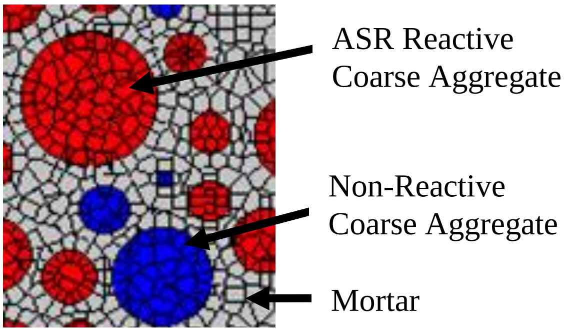



**Figure 1**: Mesh arrangement for mortar and aggregates.

As illustrated in Fig.2, for each rigid body mesh element, there are six degrees of freedom (DOF), including three translational degrees of freedom and three rotational degrees of freedom, at a certain point located in its interior. Each rigid body element is connected to its neighborhood by three springs, where two of them are shear springs and one is normal spring.

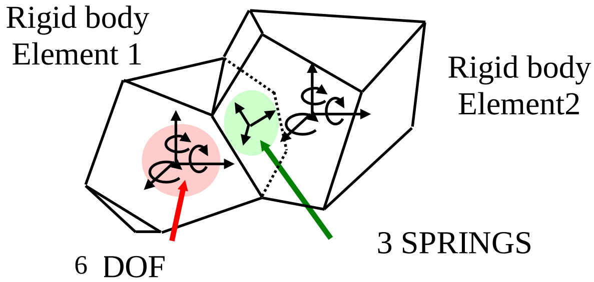



**Figure 2**: 3D RBSM mechanical model.

A constitutive model developed by Nagai et al. [8] for concrete at the mesoscale is used in this research. The initial strain was introduced in the spring element as the damage history [11].

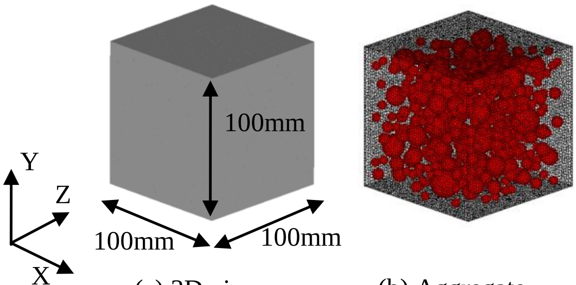
In previous research done by Eddy et al. [9], map cracking pattern in ASR expansion was successfully predicted using 3D RBSM simulation. But DEF expansion was not well simulated using simply uniform expansion. In this study, factors such as aggregate percentage and ASR reactive aggregate percentage are considered in ASR expansion, while non-uniformed expansion is introduced in DEF expansion.

**Table 1**: Model mechanical properties.

| Mortar | | | Aggregate | Interface |
|---|---|---|---|---|
| Modulus of Elasticity $E_c$ [MPa] | Tensile Strength $f_t$ [MPa] | Compressive Strength $f'_c$ [MPa] | Modulus of Elasticity $E_g$ [MPa] | Tensile Strength $f_t$ [MPa] |
| 29,290 | 2.48 | 35 | 50,000 | 1.63 |

## 2.2 GEOMETRY OF NUMERICAL MODELS

Fig. 3 shows one of the analyzed numerical models. The size of the model is 100 x 100 x 100 mm.




(a) 3D view (b) Aggregate inside model

**Figure 3**: 3D concrete model.

Aggregate size distribution is determined according to the JSCE Standard Specification for Concrete Structures. Maximum aggregate size is 20 mm. The expansion in concrete is applied by introducing the concept of expansive strain. The initial stain is introduced in expanding interfaces step by step to generate expansion. Seven cases are simulated in this research, with their mechanical properties set as represented in Table.1. Details of models in use are summarized in Table.2. Aggregate volume ratio is targeted as 30% and 15% in this simulation.

To represent the expansion generated originally from the interface between aggregate and mortar, as the ASR gel is formed around the aggregate [12], the initial strain is introduced at the interfaces between aggregate elements and mortar elements.

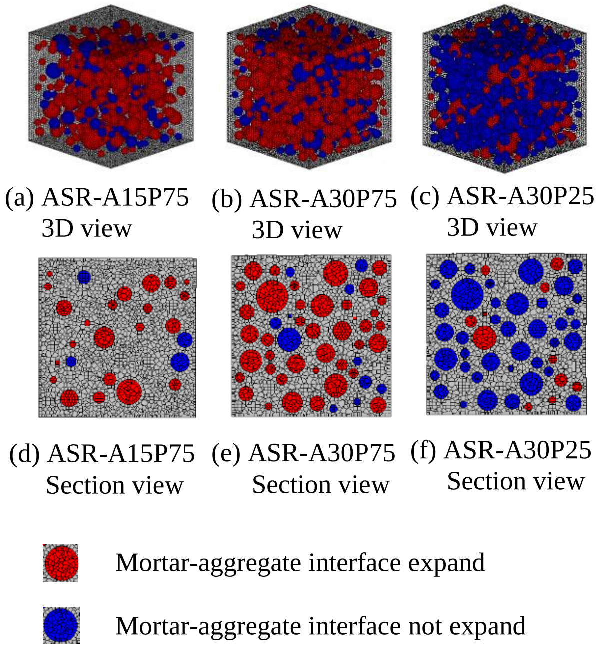
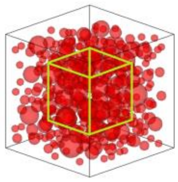



**Figure 4**: Models used in ASR expansion simulation.

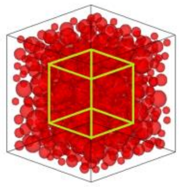
As shown in Fig. 4, three numerical models named by ASR-A15P75, ASR-A30P75, and ASR-A30P25, are considered. A15 represents the target aggregate ratio to be 15%, A30 represents the target aggregate ratio to be 30%. P75 here represents that 75% of randomly selected aggregates introduced is ASR reactive, while P25 indicates that 25% of randomly selected aggregates are ASR reactive. In Fig.4, three cases are represented, with aggregate in red color representing ASR reactive aggregate and blue color representing non-reactive aggregate. Section views are collected from the cross sections at z = 50 mm of each modal.

**Table 2**: Model expansion details.

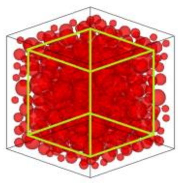
| Case | Expansion type | Aggregate Percentage | ASR Reactive Aggregate Percentage | DEF Expansion Intensified Zone |
|---|---|---|---|---|
| ASR-A15P75 | ASR | 15% | 75% | |
| ASR-A30P75 | ASR | 30% | 75% | |
| ASR-A30P25 | ASR | 30% | 25% | |
| DEF-A15I50 | DEF | 15% | | 50 x 50 x 50 mm |
| DEF-A30I50 | DEF | 30% | | 50 x 50 x 50 mm |
| DEF-A30I75 | DEF | 30% | | 75 x 75 x 75 mm |
| DEF-A30I100 | DEF | 30% | | 100 x 100 x 100 mm |



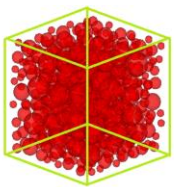
(a) DEF-A15I50 3D view



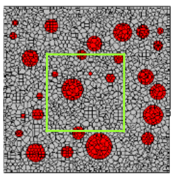
(b) DEF-A30I50 3D view



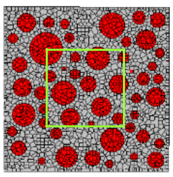
(c) DEF-A30I75 3D view



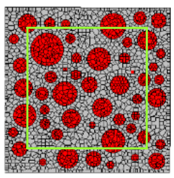
(d) DEF-A30I100 3D view



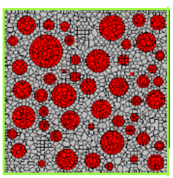
(e) DEF-A15I50 Section view



(f) DEF-A30I50 Section view



(g) DEF-A30I75 Section view



(h) DEF-A30I100 Section view



DEF expansion intensified zone

**Figure 5**: Models used in DEF expansion simulation.

For DEF, to represent the mortar expansion, the initial strain is introduced at the interfaces between mortar and mortar elements. Here non-uniformed expansion is introduced considering non-uniformed maximum temperature during curing. As DEF is a phenomenon closely relative to curing temperature [13-14], the inner part of concrete which suffered from relatively higher curing temperature may expand more than the surrounding mortar. Four numerical models named DEF-A15I50, DEF-A30I50, DEF-A30I75, and DEF-A30I100, are considered, as showing in Fig.5. The aggregate ratio is labeled in the same way as in ASR cases. I100 indicate that the whole model is uniformly expanding, I75 indicate that center 75 x 75 x 75 mm part is given intensified expansion, and I50 indicate that the center 50 x 50 x 50 mm part is given intensified expansion.

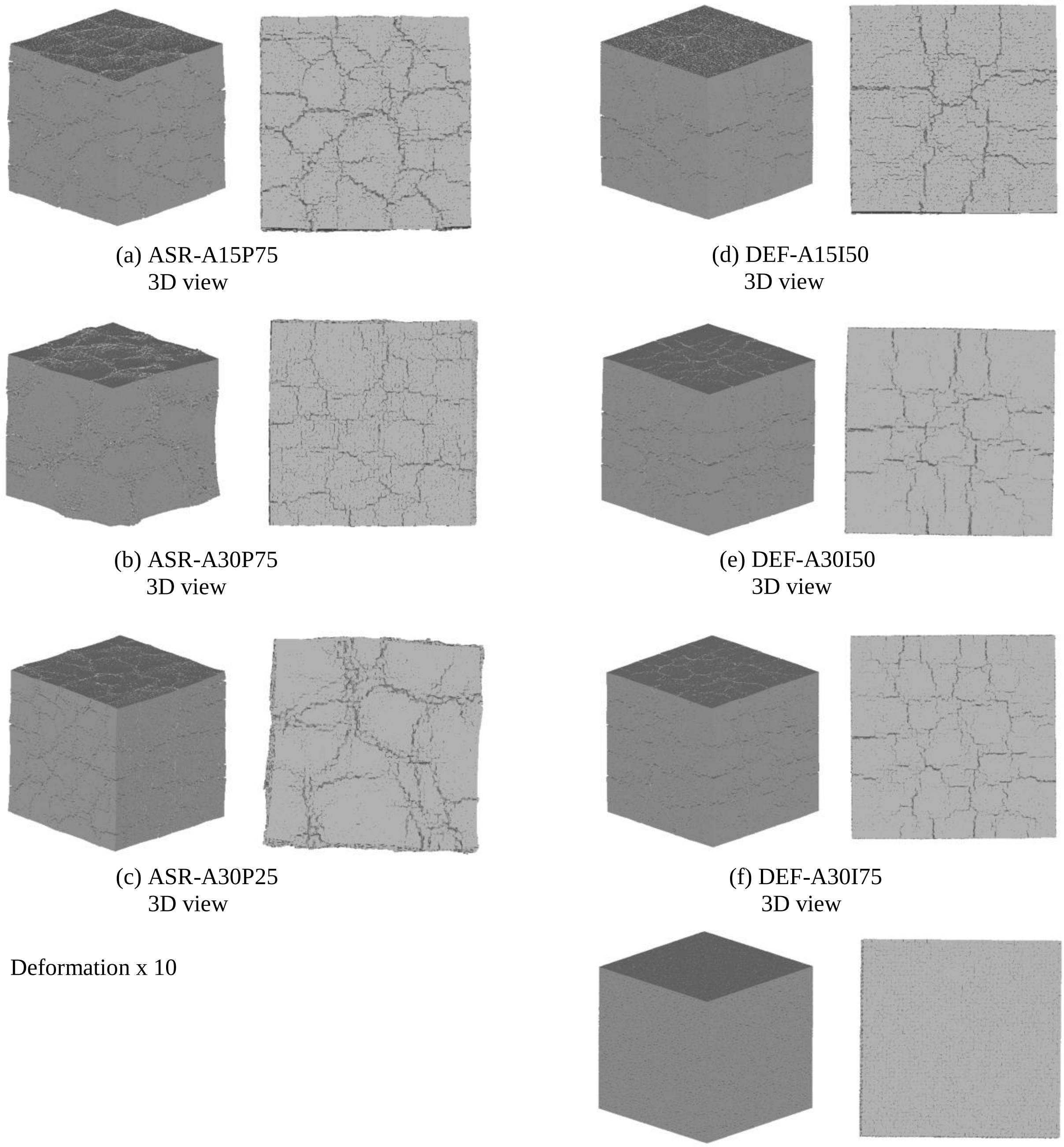
Global expansion is measured by the distant change of elements located at the center of the left surface and the center of the right surface, separately, in percentage. The internal expansion is given until the target global expansion obtained 0.5% in this study.

## 3 SIMULATION OF CRACKING PATTERN DUE TO ASR AND DEF EXPANDED CONCRETE

### 3.1 SURFACE CRACKS

Fig. 6 summarized all the 3D representations of surface crack listed in Table 2, in 10 times of deformation. All cases have an expansion of around 0.5% one-dimensionally in length. Surface cracking results show different reaction to different given expansion mechanism. All cases except uniformed expanded DEF case have generated localized cracks in a map pattern on the surface.

Comparing Fig. 6(a), Fig. 6(b) and Fig. 6(c), in ASR expansion, with less percentage of aggregate which generates expansion, cracks become more concentrated, presenting more scatter but more localized map cracks. This can be seen in both decreasing reactive aggregate percentage and decreasing total aggregate percentage.



(a) ASR-A15P75
3D view

(d) DEF-A15I50
3D view

(b) ASR-A30P75
3D view

(e) DEF-A30I50
3D view

(c) ASR-A30P25
3D view

(f) DEF-A30I75
3D view

Deformation x 10

(g) DEF-A30I100
3D view

**Figure 6**: 3D expansion result at 0.5% of one-dimensional expansion.

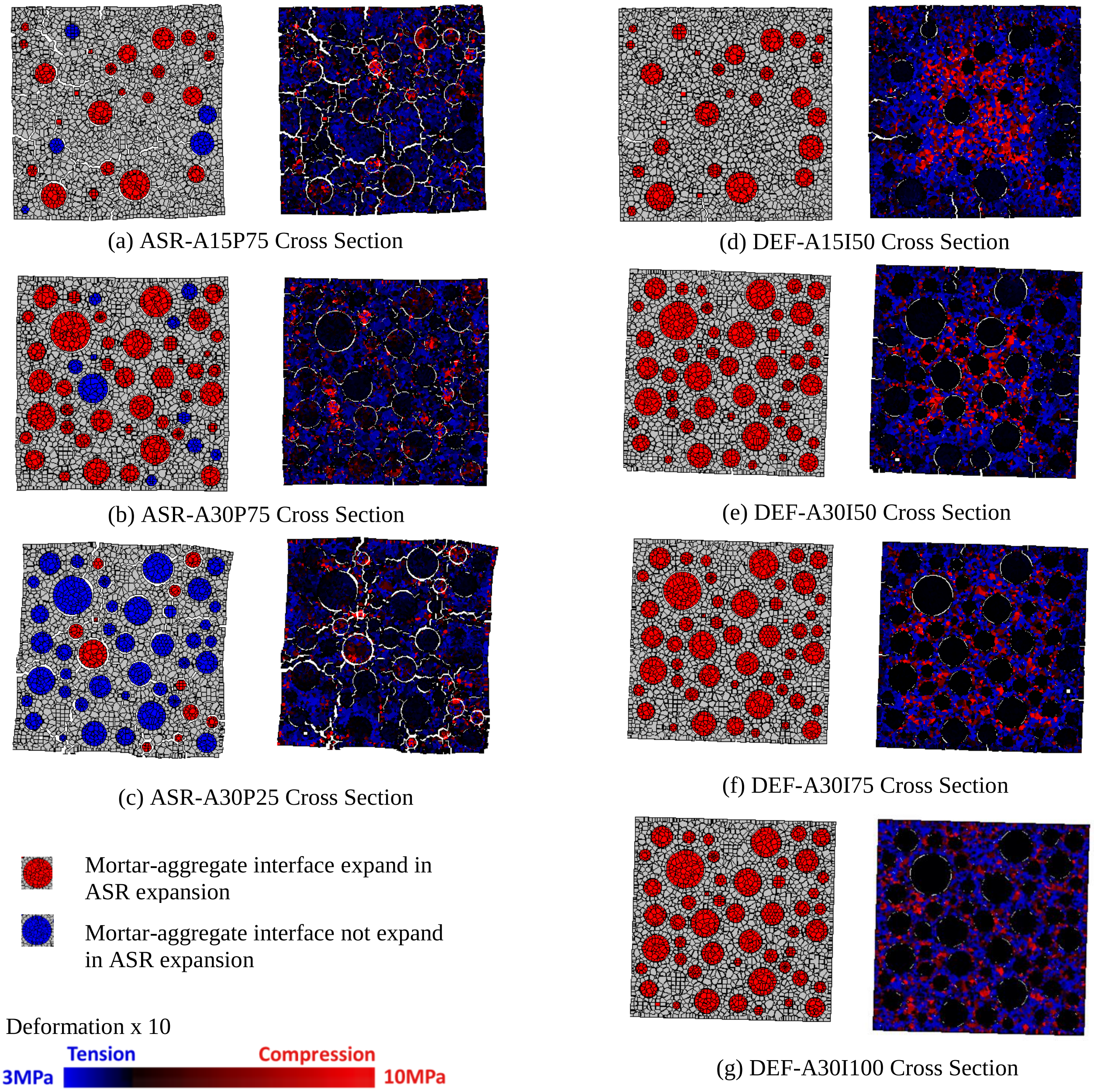



**Figure 7**: Internal crack and stress condition at 0.5% of one-dimensional expansion.

In DEF expansion, the same result of no localized cracking shown in uniformed expansion case (Eddy L. et al. [9]) is reached, while the localized surface crack in map pattern can be seen in all cases with the application of intensified expanse in the inner part of the model. This result indicates that non-uniform expansion is an appropriate approach in simulating DEF cracking pattern. Aggregate percentage here does not have a significant influence in the localization of surface cracking.

## 3.2 Internal Cracks and Stress Conditions

Inner cracks and stress here are presented to better understand the generation of surface cracking pattern, as shown in Fig.7. Section views collected from the cross sections at z = 50 mm are chosen.

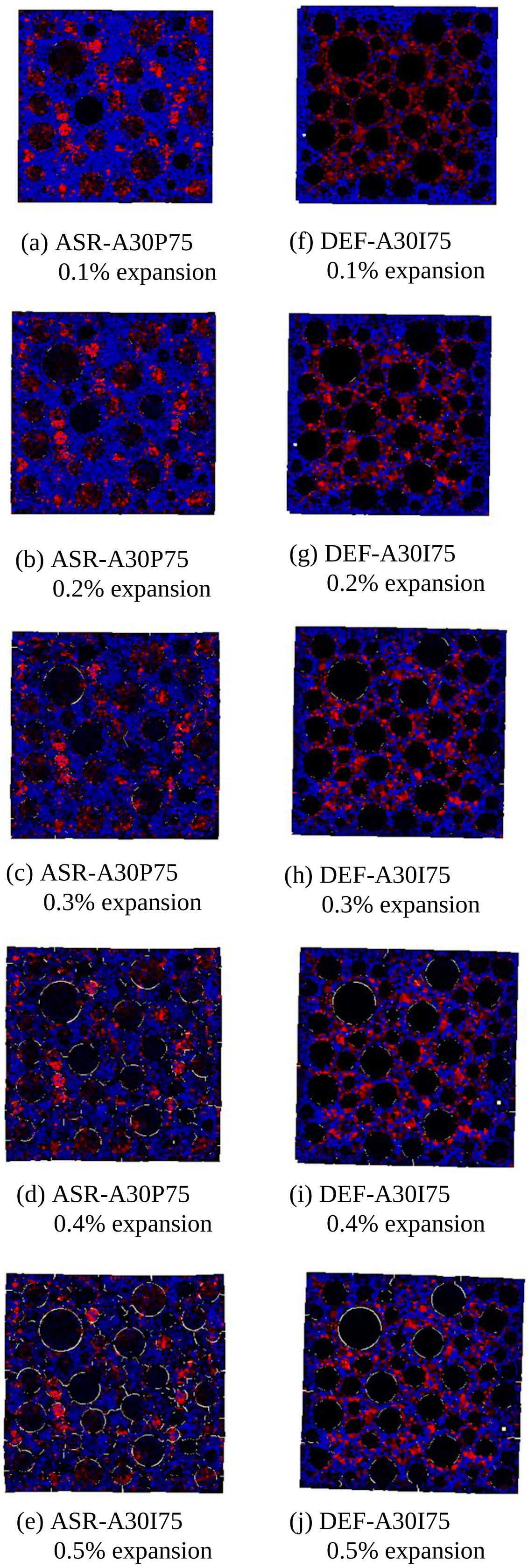



**Figure 8**: Change of internal crack and stress condition in ASR-A30I75 and DEF-A30I75.

For ASR expansion, presenting in Fig.7 (a) to (c), inner cracks are generated between aggregates. For some aggregates located close to the surface, cracks penetrated to the outer surface and presented as surface map cracks shown in 3D views in Fig.6. Though here in the section view some empty space do appears between aggregate and surrounding mortar, but this is not considered as cracks, since it only represents springs elongation due to initial strain given.

Aggregates in ASR expansion, especially ASR reactive ones, are under compression, while the surrounding mortar elements are generally under tension.

At the same global expansion ratio (0.5% one-dimensionally), inner cracking and deformation become much more significant and localized when less reactive aggregates are introduced, which is corresponded with the trend in surface cracking.

For DEF with intensified expanding in the center, presenting in Fig.7 (d) to (f), cracks only generated nearby surfaces, with gaps generated around aggregates. In compare, for uniform expansion case, Fig.7 (g), no localized inner crack could be recognized by naked eyes.

Neither changing aggregate ratio nor changing expansion intensified zone range has significant influence in the inner cracking pattern. All cases with inner expansion intensified zone have distinct expansion behavior with simple uniform expanded one.

Mortar elements, especially in the expansion intensified zone, partially under compression. Mortar elements outside expansion intensified zone generally under tension due to the differences in deformation between inner and surrounding part. Aggregates are separated from the mortar parts and not stressed.

To investigate the changing of internal cracking and stress condition, Fig. 8 shows the cross sections at different global expansion levels in ASR-A30P75 and DEF-A30I75.

As shown in Fig.8 (a) to (e), for ASR expansion, as the initial strain is given between reactive aggregates and surrounding elements, the reactive aggregates are under compressive stress, while the mortar part is under tensile stress. Along with deformation, cracks started to generate between aggregates.

In Fig.8 (f) to (j), for DEF expansion, stress mainly distributed only in the mortar. With the uniformed expansion, compressive stress and tensile stress uniformly distributed in all mortar parts. Gaps are generated between mortar and aggregates as deformation happens. No stress further transforms into aggregates once they are detached with mortar. The whole model increasing its volume without generating inner cracks. With center intensified zone applied, the inner part which expanse more than the surrounding, suffer from compressive strength, while the mortar located in outer part mainly suffer from tensile stress. Along with deformation, cracks start to generate in the tensile zone, which causing surface cracks in the 3D views. However, no localized crack could be found in the compressive zone.

## 4 CONCLUSIONS

Base on the simulation and analysis of concrete expansion due to different causes by 3D RBSM, the following conclusions can be drawn:

1. Surface map pattern cracking are well simulated in both ASR and DEF expansion simulation, separately. Center intensified expanding in DEF simulation is an appropriate approach in simulating DEF cracking pattern.

2. For ASR expansion, inner cracking and stress simulation revealed that inner parts are also damaged in ASR expansion. Both surface cracks and inner cracks become more localized with less percentage of ASR reactive aggregate introduced.

3. For DEF, map cracks occurred with inner intensified expansion introduced. The inner part of DEF expanded models does not have localized crack in the center part. However, aggregate percentage and expansion intensified range does not show significant influence in expansion behavior.

4. Internal stress condition revealed the clear different mechanisms applied in ASR and DEF expansion. 3D RBSM is a feasible approach in simulating concrete expansion due to different causes numerically, with specialties in analyzing inner crack and stress conditions.

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