UNIVERSITY OF TOKYO

Simulation of Concrete Cracking Pattern Combining DEF and ASR Expansion

by

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A thesis submitted in partial fulfillment for the degree of Master

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Chapter 1

Simulation of Cracking Pattern Of ASR and DEF Expanded Concrete

1.1 General

In this chapter, three-dimensional expanded simulations are carried out on concrete models in free condition. The purpose of this study is for the prediction of the behavior during the expansion of concrete, especially the cracking pattern and stress distribution.

1.2 Cracking Pattern caused by Pure ASR Expansion

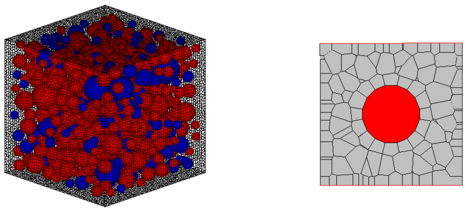
1.2.1 ASR Expansion Simulation of Single Aggregate Case

In this section, simulation of ASR expansion on a single aggregate case in size only 10x10x10mm is presented.

Since this model is very small and simple, it is easier to analyze the behavior of ASR expansion in very small scale around coarse aggregate.

The expanse is generated at the location of interfaces between mortar and aggregate, to introduce the expansion, as introduced in chapter 2.

0.001 initial strain is introduced in each step at the interfaces between the aggregate and paste elements. Totally 20 steps of expansion are done.



(A) 3D View

(B) Cross Section View

Figure 1.1: Single Aggregate Case in Size 10x10x10mm (Deformation x 10)

From the Figure 1.2, we can see that step by step with initial stain introducing into the model, distance appears between aggregate and the surrounding element at first, which theoretically should be filled by ASR gel, the product of ASR reaction.

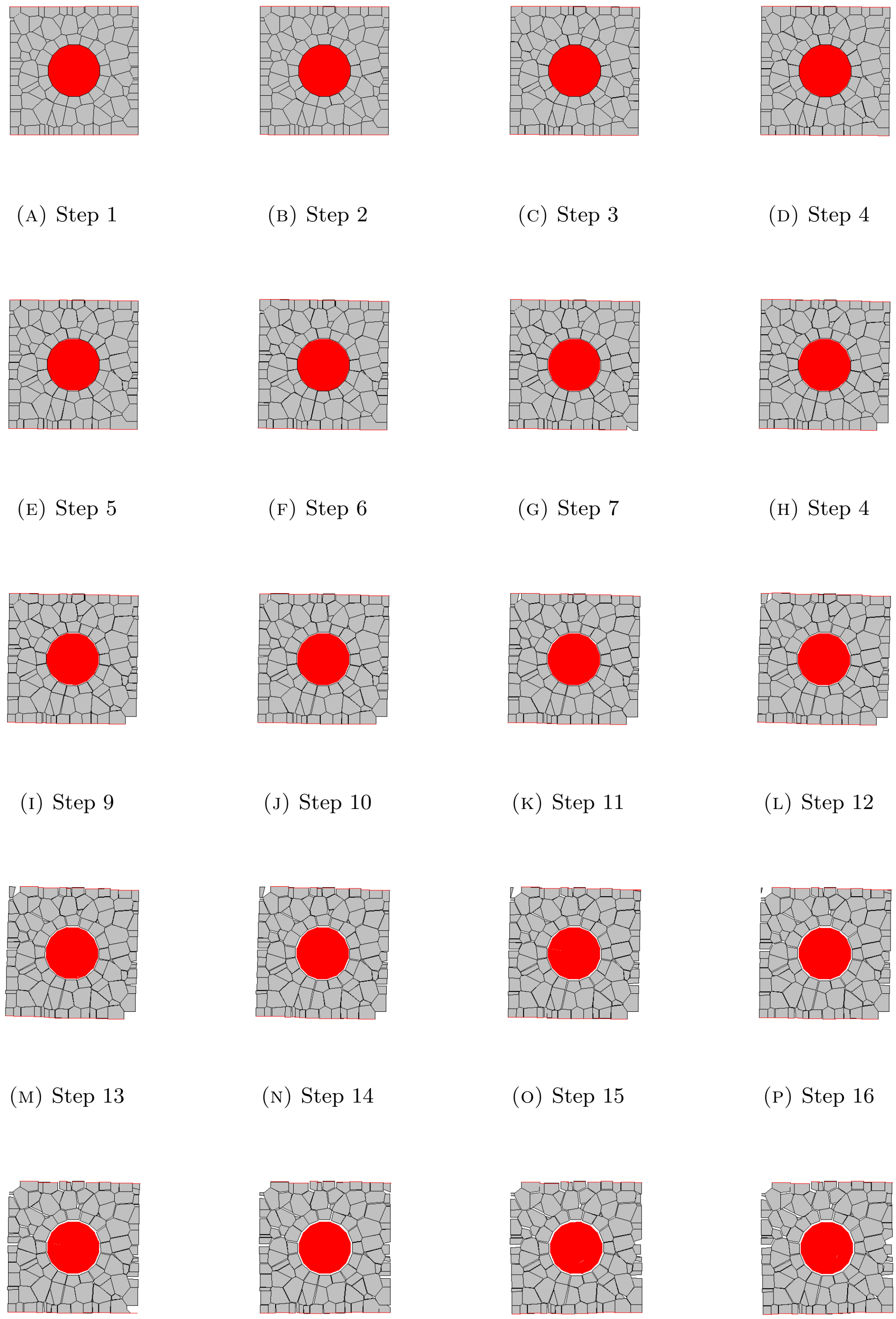
After, by the influence of the unbalanced force start from the aggregate-mortar interfaces, elements surround it also react. Cracks start to generate from aggregate to the paste surrounding it.

The total volume of this small model is increasing step by step, while until the step 20 the model expanded 0.1625% one dimensionally.

Also, the Inner Stress condition for each step is collected and shown in Figure 1.3, which can also reveal many details in the expanding procedure.

From step 1 compressive stress is generated in and one layer around the reactive aggregate, due to the initial strain added to the reactive interfaces. While other paste elements located around reactive aggregate reacted in tension status.

This very small size simple example shows logically our method of adding initial strain to generate ASR expansion should work in the way we assumed.



(A) Step 1 (B) Step 2 (C) Step 3 (D) Step 4

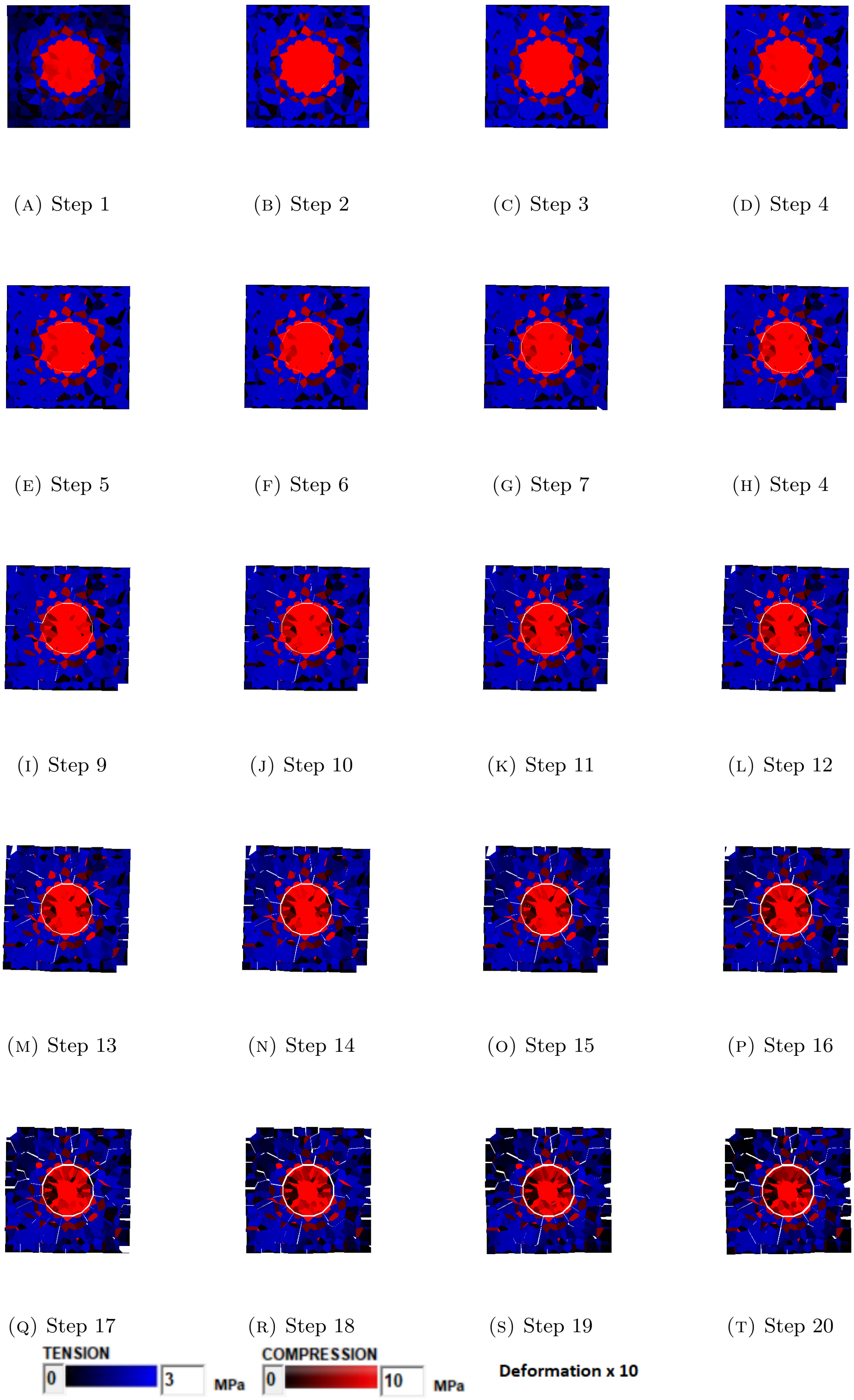
(E) Step 5 (F) Step 6 (G) Step 7 (H) Step 4

(I) Step 9 (J) Step 10 (K) Step 11 (L) Step 12

(M) Step 13 (N) Step 14 (O) Step 15 (P) Step 16

(Q) Step 17 (R) Step 18 (S) Step 19 (T) Step 20

FIGURE 1.2: Cross Section in Each Step for ASR 10x10x10mm Case (Deformation x 10)



(A) Step 1 (B) Step 2 (C) Step 3 (D) Step 4

(E) Step 5 (F) Step 6 (G) Step 7 (H) Step 4

(I) Step 9 (J) Step 10 (K) Step 11 (L) Step 12

(M) Step 13 (N) Step 14 (O) Step 15 (P) Step 16

(Q) Step 17 (R) Step 18 (S) Step 19 (T) Step 20

FIGURE 1.3: Internal Stress in Each Step for ASR 10x10x10mm Case (Deformation x 10)

1.3 Cracking Pattern caused by Pure ASR Expansion

1.3.1 Single ASR Expansion Simulation

In this section, the process of simulated one ASR expansion is present. The expanse is generated at the location of interfaces between mortar and reactive aggregate, to introduce the expansion, as introduced in chapter 2.

For usually the case not all aggregate inside concrete structure are ASR reactive aggregate, here only partial of aggregates are selected to be ASR reactive and will be givin initial strain in expansion steps to simulate ASR expansion.

This single example case has been choosing here use the model in the dimension of 100x100x100mm, with 30% aggregate, of which 75% are ASR reactive. Aggregate in Figure 1.36 in red color is assumed as ASR reactive, while aggregate in blue color is assumed as non-reactive aggregate.

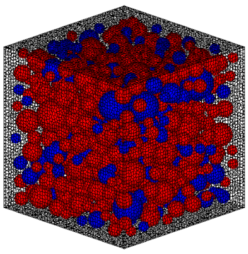


FIGURE 1.4: 30% Coarse Aggregate

Table. Aggregate consistent(if we have it)

To simulate ASR expansion, an initial strain of 0.001mm is given in each step, for totally 20 steps expansion. Before and after expansion, the distance of element between 2 elements is recorded to gauge the gloal expansion. These two element selected here are the middle element in the left surface of model and the middle element in the left surface of model.

With the increasing of initial strain giving, the global expansion also gradually increasing. After 20 steps of ASR expansion, the model here reached 0.4223% expansion(one-dimensionally). Characteristic ASR map cracking pattern can be seen on the surface of the expanded concrete model in Figure 1.6.

As can be seen in Figure 1.7 the internal stress from step 1 to 20, along with the increasing of giving initial strain, unbalanced force present in the concrete model, compressive stress (in red color) generated and distributed especially in coarse aggregates. Gradually crack

Step	Expansion	Step	Expansion
1	0.000136	11	0.002140
2	0.000314	12	0.002358
3	0.000501	13	0.002582
4	0.000695	14	0.002812
5	0.000894	15	0.003049
6	0.001096	16	0.003278
7	0.001301	17	0.003536
8	0.001507	18	0.003767
9	0.001715	19	0.003989
10	0.001924	20	0.004223

TABLE 1.1: Expansion in Each Step for A30 P75 Case 3

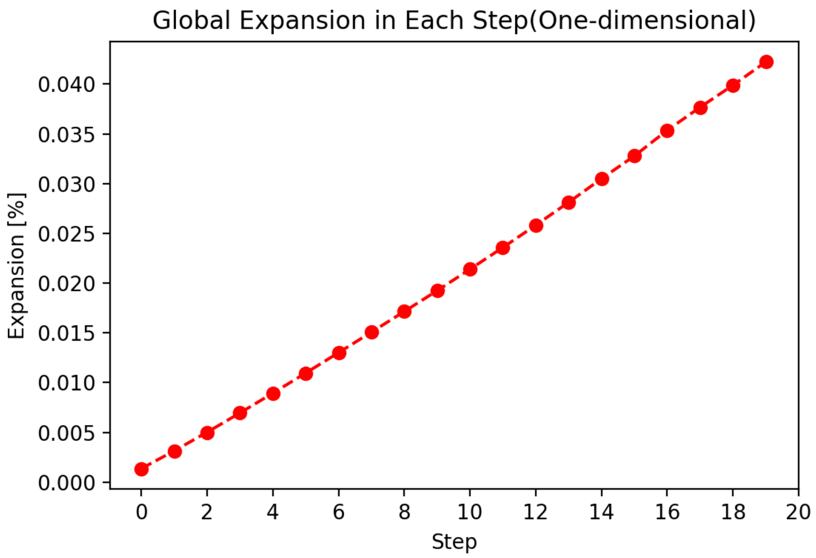


FIGURE 1.5: Global Expansion vs. Step

generated around the aggregate, penetrated and finally linked between aggregates and reached surface of the model.

In Figure 1.8 shows the inner crack distribution right after 20 steps of ASR expansion. The cracked interfaced which larger than 0.03mm are colored in orange, to present the distribution of internal crack three dimensionally. With 0.4223% of one dimensional global expansion, cracks over 0.03mm are distributed relatively uniformed inside the model.

For analyzing the behavior of expansion caused by ASR numerically, cracked interfaces are summarised in different crack width scale, shown in Table 1.15. The maximum crack width, in this case, is in range of 0.01-0.03mm, while most of the cracks are under 0.001mm. The ability of RBSM simulation in numerically analysis distribution of cracked interfaces gives us information that with difficulties to obtain in experimental

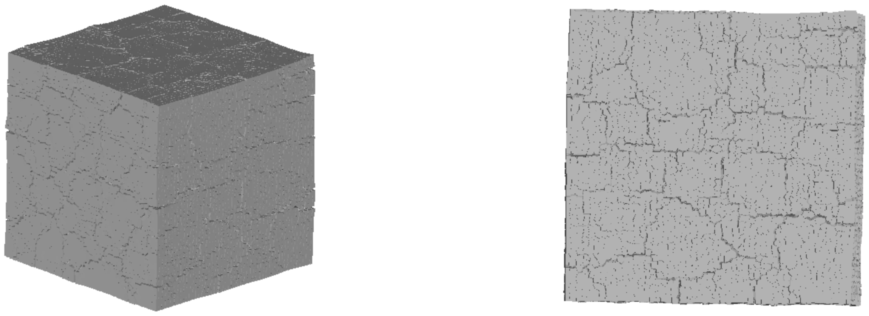


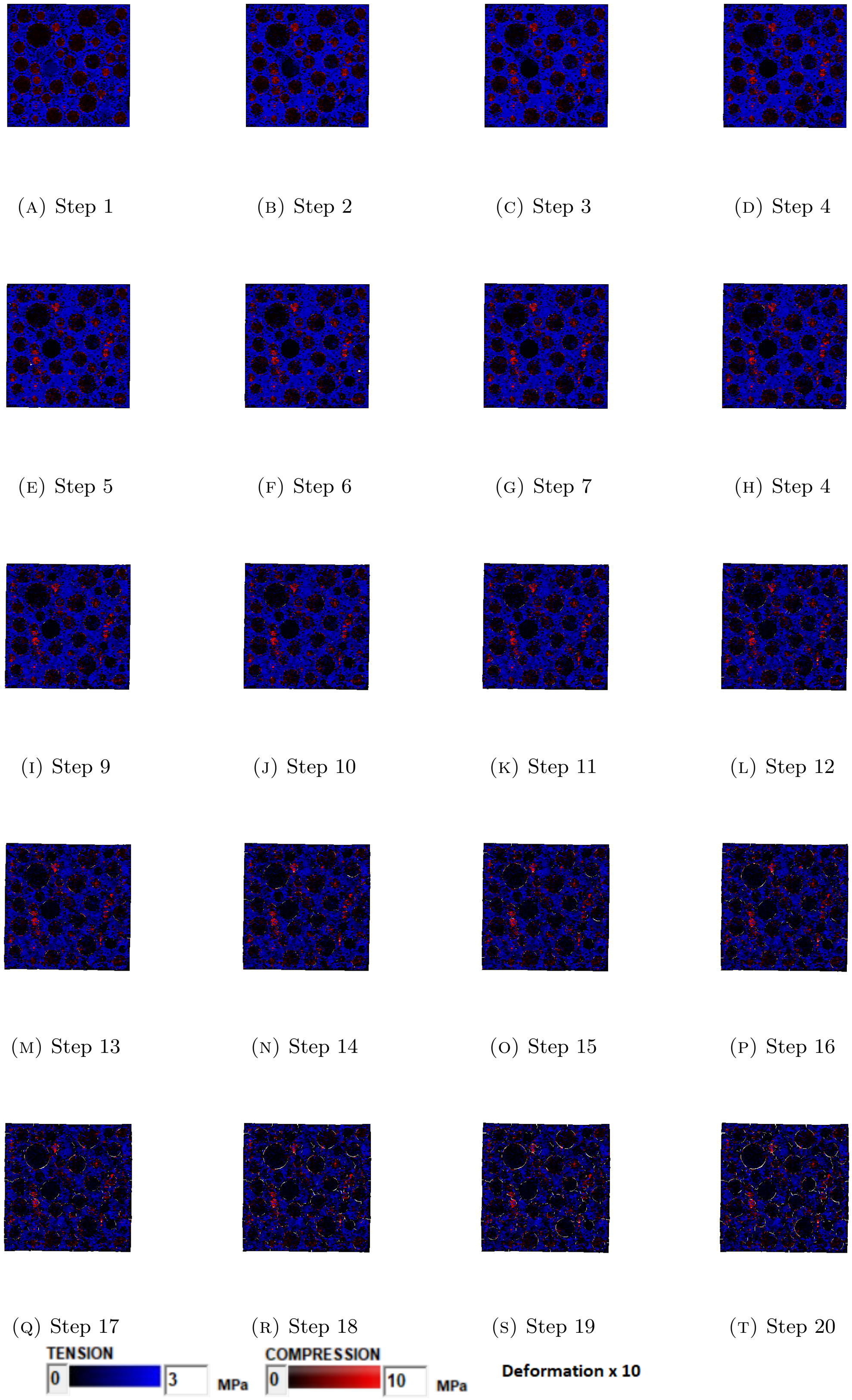
FIGURE 1.6: 3D Surface Cracks, 0.4223% Expansion (Deformation x 10)

tests. These numbers will be compared with simulations given different global expansion ratio, different aggregate consistent, even different mechanism.

Crack Width [mm]	Total Cracked Interfaces
0.00000 - 0.00005	316744
0.00005 - 0.00010	286704
0.00010 - 0.00020	263943
0.00020 - 0.00050	234672
0.00050 - 0.00100	183238
0.00100 - 0.00300	131553
0.00300 - 0.01000	42432
0.01000 - 0.03000	275
0.03000 - 0.10000	0
0.1000+	0

TABLE 1.2: Crack Summarised by width

In Figure 1.8, inner cracking interfaces with over 0.03mm are colored in orange. From this illustration, it can be seen that the cracks are distributed relatively uninformed in the expanded model, which is co-insistent with the condition shown in the 2D inner section.



(A) Step 1 (B) Step 2 (C) Step 3 (D) Step 4

(E) Step 5 (F) Step 6 (G) Step 7 (H) Step 4

(I) Step 9 (J) Step 10 (K) Step 11 (L) Step 12

(M) Step 13 (N) Step 14 (O) Step 15 (P) Step 16

(Q) Step 17 (R) Step 18 (S) Step 19 (T) Step 20

FIGURE 1.7: Internal Stress in Each Step for A30 P75 Case 3 (Deformation x 10)

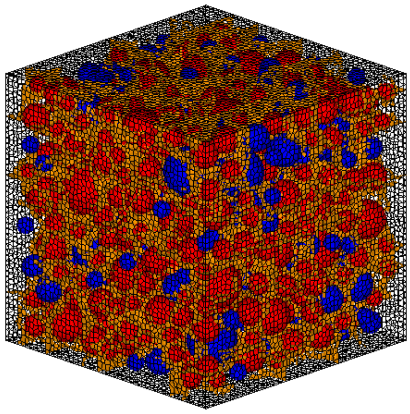


FIGURE 1.8: 3D Inner Cracking larger than 0.03mm

1.3.2 Expansion Ratio Related to Behavior of Concrete During ASR Expansion

In this section, the relationship between given initial strain, final expansion and behavior during expansion is discussed.

Model in size of 100x100x100mm is in used, with 30% Aggregate (75% of which is ASR reactive).

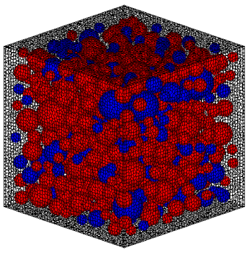


FIGURE 1.9: 30% Coarse Aggregate

Expansion is carried out with initial strain given in each step various from 0 to 0.003. Total expansion step are set as 20 steps same for all cases. From the Table 1.3 can be seen that with the increasing of giving initial strain in each step, the global expansion reached in step 20 also increased. Non-damage model is using here for compare.

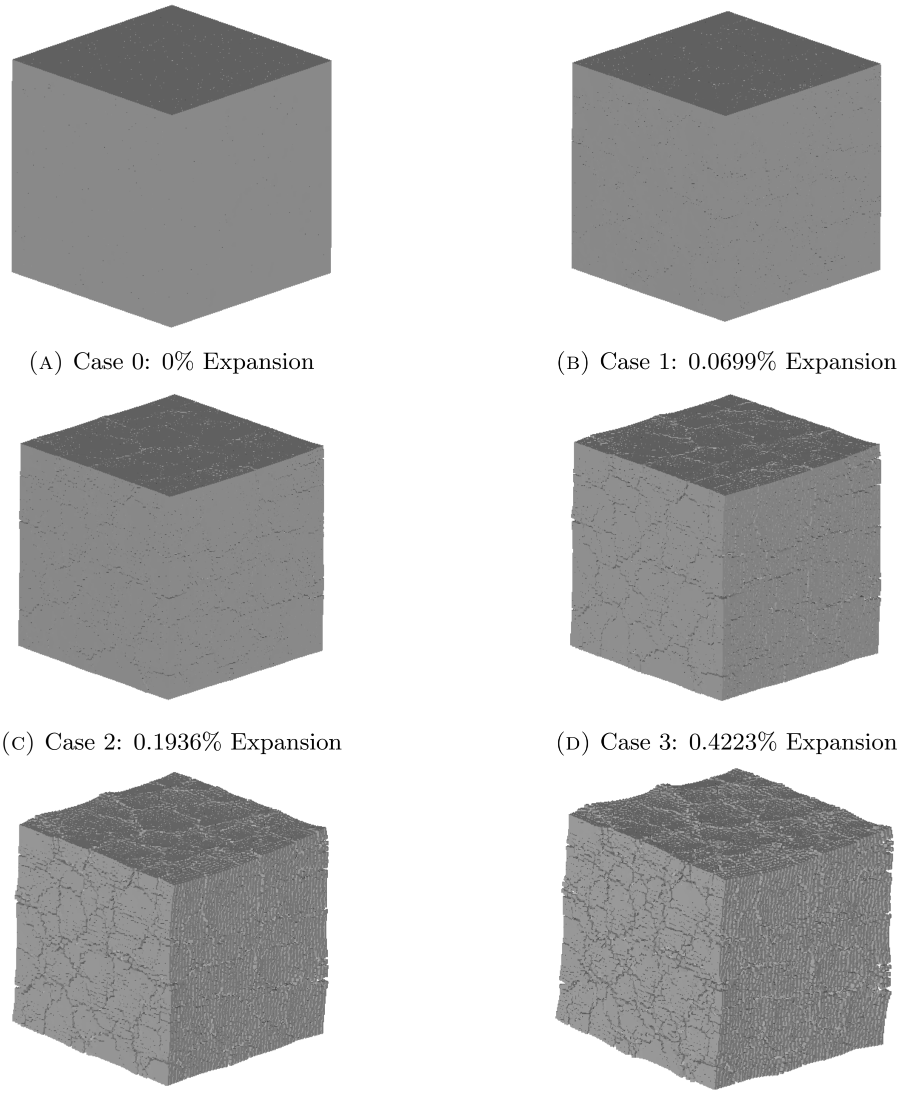
Aggregate Ratio[%]	Reactive Aggregate Ratio[%]	Initial Strain (Each Step)	Expanding Steps	Final Expansion [%]
30	75	0	0	0
30	75	0.0002	20	0.0699
30	75	0.0005	20	0.1936
30	75	0.001	20	0.4223
30	75	0.002	20	0.8832
30	75	0.003	20	1.3224

TABLE 1.3: One Dimensional Expansion Ratio in Single ASR Model Simulation

Figure plot of inital strain vs. global expansion ratio

As shown in Figure 1.10 and Figure 1.11, it is clear that with the increase of global expansion ratio, the cracking can be seen on the surface of concrete model become much significant. However, the map cracking pattern does not change much comparing the expanded models in different expansion ratio.

This also indicated that our simulation can still predict the map cracking behavior for ASR expansion in different deterioration levels.



(A) Case 0: 0% Expansion

(B) Case 1: 0.0699% Expansion

(C) Case 2: 0.1936% Expansion

(D) Case 3: 0.4223% Expansion

(E) Case 4: 0.8832% Expansion

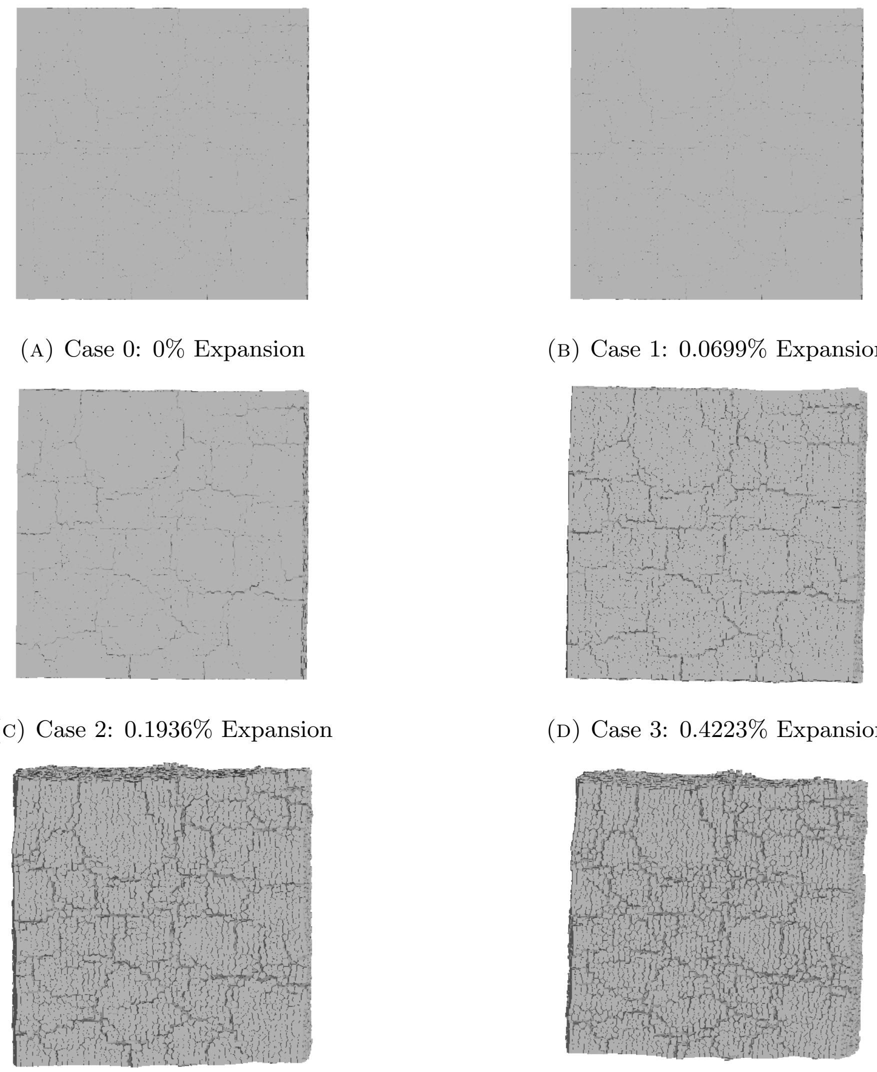
(F) Case 5: 1.3224% Expansion

Figure 1.10: 3D Surface Cracks (Deformation x 10)

It is possible that the position where large crack generated is determined by other factors, for example, the location of coarse aggregate.

By comparing the inner cracking condition in Figure 1.12, it can be seen that start from 0.1936% of one-dimensional global expansion, cracks larger than 0.03mm are generated and able to be recognizable by the naked eye. With the increase of global expansion ratio, the inner crack generally increases, distributed relatively uniform in all inner part of the expanded model. This cracking pattern will be compared with ASR expansion in different reactive aggregate ratio simulation and also DEF simulations.

In Figure 1.13, the internal stress distribution in some middle step and last expansion step are shown. By increasing the initial strain giving to present ASR expansion in each



(A) Case 0: 0% Expansion

(B) Case 1: 0.0699% Expansion

(C) Case 2: 0.1936% Expansion

(D) Case 3: 0.4223% Expansion

(E) Case 4: 0.8832% Expansion

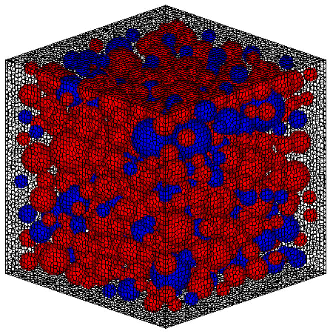
(F) Case 5: 1.3224% Expansion

FIGURE 1.11: 3D Surface Cracks (Single Side View, Deformation x 10)

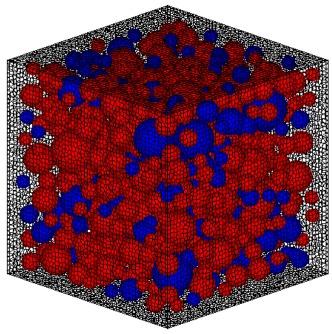
step, the expansion developed more rapidly and more inner cracks generated as well as outer cracks.

This suggests deteration caused by ASR not only causing the aesthetic problem on the surface of the concrete structure but also indicate structually damage inside.

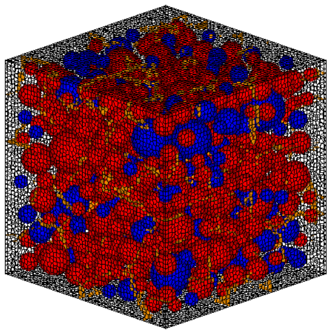
By visualizing the inner crack, we can confirm that the inner part of the ASR-damaged concrete model also deteriorated. As the increasing of global expansion, inner cracks gradually increase its number and volume, in cases over 0.8% global expansion, crack with a width larger than 0.03mm almost covered all inner part of the expanded model.



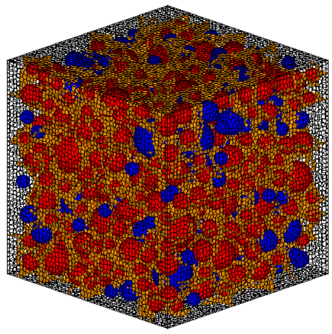
(A) Case 0: 0% Expansion



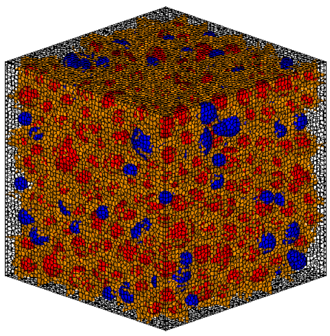
(B) Case 1: 0.0699% Expansion



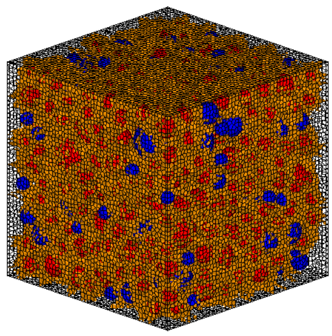
(C) Case 2: 0.1936% Expansion



(D) Case 3: 0.4223% Expansion

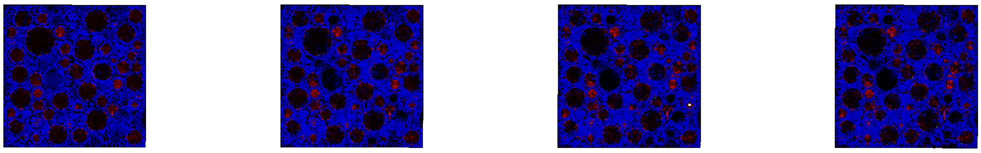


(E) Case 4: 0.8832% Expansion

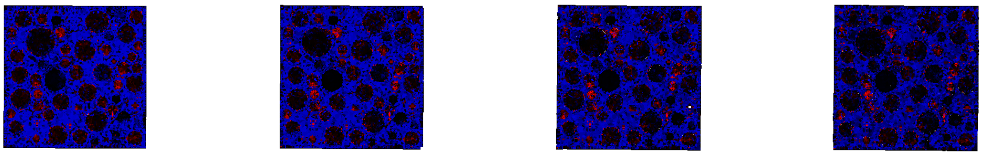


(F) Case 5: 1.3224% Expansion

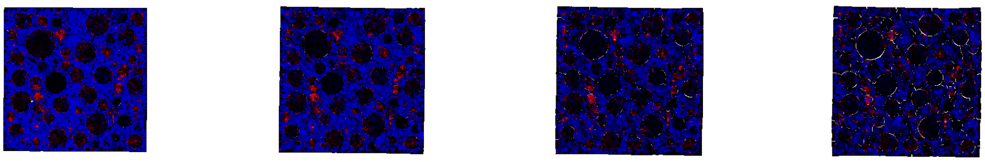
FIGURE 1.12: 3D Inner Crack Width Larger than 0.03mm



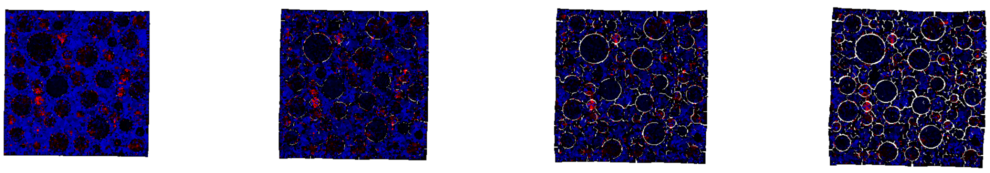
(A) 0.0699% Expansion Internal Stress Step 5
(B) 0.0699% Expansion Internal Stress Step 10
(C) 0.0699% Expansion Internal Stress Step 15
(D) 0.0699% Expansion Internal Stress Step 20



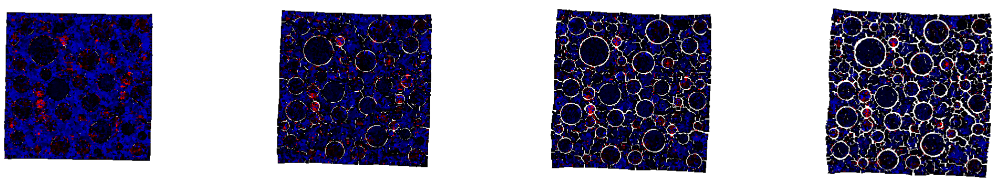
(E) 0.1936% Expansion Internal Stress Step 5
(F) 0.1936% Expansion Internal Stress Step 10
(G) 0.1936% Expansion Internal Stress Step 15
(H) 0.1936% Expansion Internal Stress Step 20



(I) 0.4223% Expansion Internal Stress Step 5
(J) 0.4223% Expansion Internal Stress Step 10
(K) 0.4223% Expansion Internal Stress Step 15
(L) 0.4223% Expansion Internal Stress Step 20



(M) 0.8832% Expansion Internal Stress Step 5
(N) 0.8832% Expansion Internal Stress Step 10
(O) 0.8832% Expansion Internal Stress Step 15
(P) 0.8832% Expansion Internal Stress Step 20



(Q) 1.3224% Expansion Internal Stress Step 5
(R) 1.3224% Expansion Internal Stress Step 10
(S) 1.3224% Expansion Internal Stress Step 15
(T) 1.3224% Expansion Internal Stress Step 20

FIGURE 1.13: Generation of Internal Stress and Inner Cracks for ASR Expansion to Step 20(Final Expansion Step, Deformation x 10)

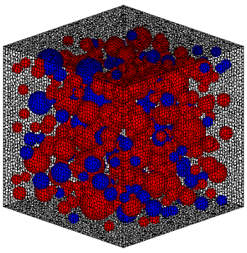
1.3.3 Aggregate Ratio Related to Behavior of Concrete During ASR Expansion

In this section, the relationship between aggregate ratio and behavior during expansion is discussed.

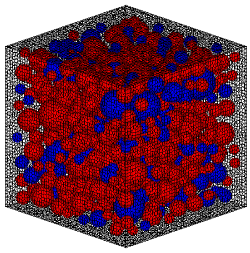
Expansion simulation result between 15% coarse aggregate model and 30% coarse aggregate model is compared here to analysis how the change in aggregate percentage influence the cracking pattern in different expansion ratio.

To eliminate the influence of ASR reactive aggregate percentage, both 15% coarse aggregate model and 30% coarse aggregate model discussed here in this section are set with 75% ASR reactive aggregate and 25% non-reactive aggregate.

ASR reactive coarse aggregate are colored in red, while non-reactive aggregate is colored in blue here. As exactly same model is used, the location of all aggregates are kept exactly the same for different percentage ASR reactive aggregare cases.



(A) 15% Coarse Aggregate



(B) 30% Coarse Aggregate

FIGURE 1.14: Coarse Aggregate Percentage

After modeling, similar ASR expansion simulations are carried out in the same way discribed in the previous section. Initial strain is giving to the interfaces between ASR reactive aggregate and paste, various from 0 to 0.003mm in each step to reach different level of global expansion in step 20.

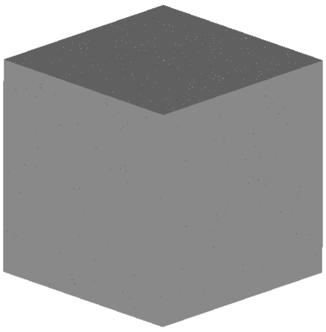
From Table 1.4 can be seen that with same expansion step and same initial strain given in each step, the global expansion of with more coarse aggregate (A30 cases here) is higher than less coarse aggregate cases (A15 cases here). As coarse aggregate ratio increased, ASR reactive interfaces are also increased, which suggested the reason for achieving larger global expansion in higher coarse aggregate cases.

This difference becomes more significant as the increasing of initial strain in each step, indicate that the amount of global expansion is not only depended on the amount of initial strain giving but also affected by other factors.

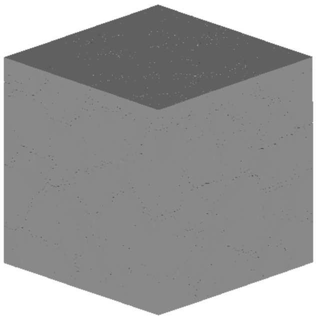
Figure, plot of inital strain vs. global expansion ratio

Initial Strain (Each Step)	Expanding Steps	A15 Final Expansion	A30 Final Expansion[%]
0	0	0	0
0.0002	20	0.0699	0.0699
0.0005	20	0.1364	0.1936
0.001	20	0.3051	0.4223
0.002	20	0.6290	0.8832
0.003	20	0.9243	1.3224

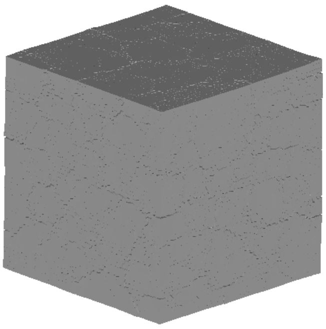
Table 1.4: One Dimensional Expansion Ratio in Single ASR Model Simulation



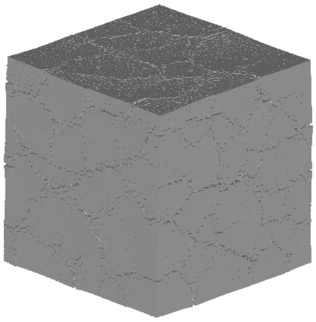
(a) Case 0: 0% Expansion



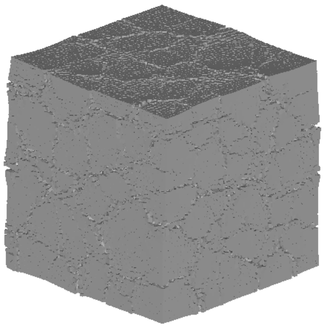
(b) Case 1: 0.0699% Expansion



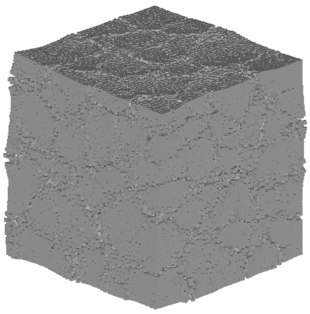
(c) Case 2: 0.1364% Expansion



(d) Case 3: 0.3051% Expansion



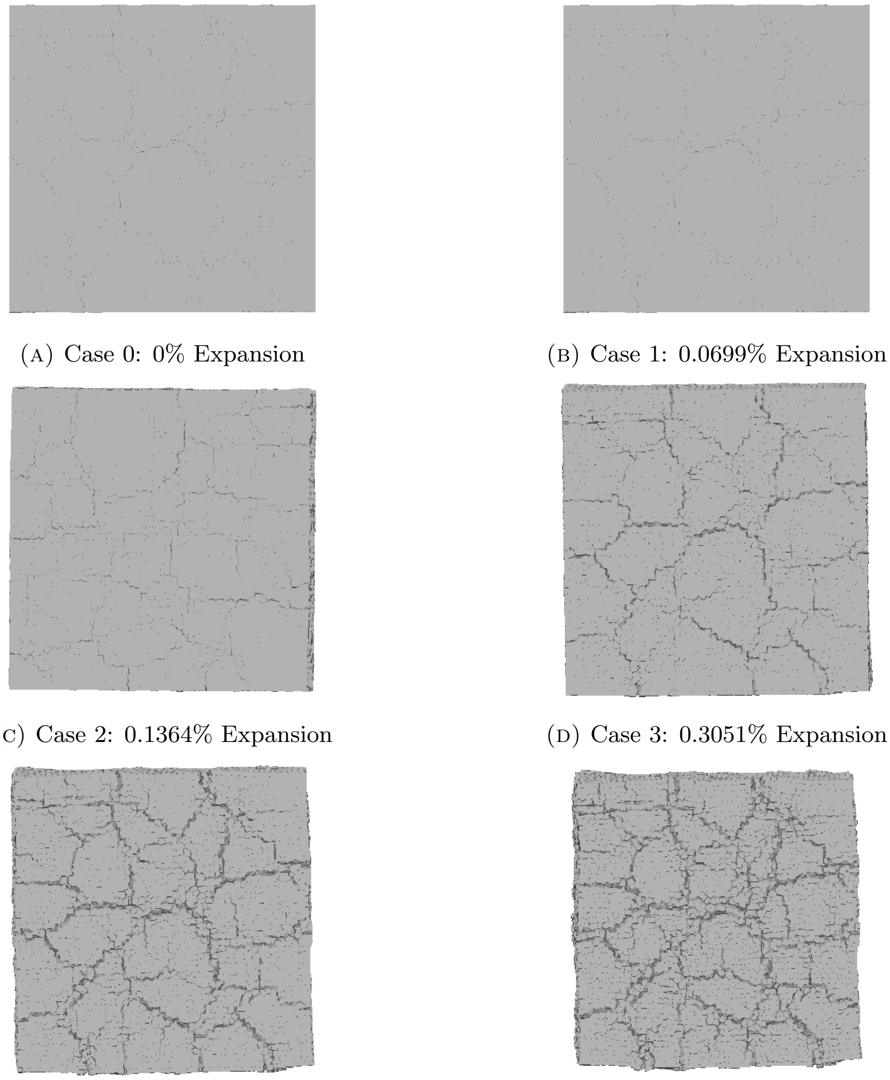
(e) Case 4: 0.629% Expansion



(f) Case 5: 0.9243% Expansion

Figure 1.15: 3D Surface Cracks (Deformation x 10)

Figure 1.15 and Figure 1.16 show surface crack pattern after ASR expansion of 15% coarse aggregate cases.



(A) Case 0: 0% Expansion

(B) Case 1: 0.0699% Expansion

(C) Case 2: 0.1364% Expansion

(D) Case 3: 0.3051% Expansion

(E) Case 4: 0.629% Expansion

(F) Case 5: 0.9243% Expansion

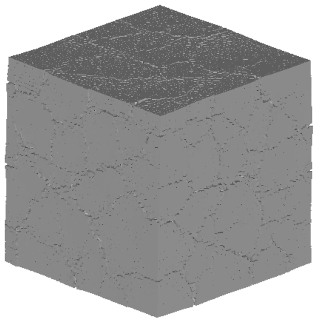
FIGURE 1.16: 3D Surface Cracks (Single Side View, Deformation x 10)

Here 2 cases from 15% coarse aggregate model and 30% coarse aggregate model in relatively close global expansion rate are compared to show the influence of coarse aggregate ratio on cracking pattern.

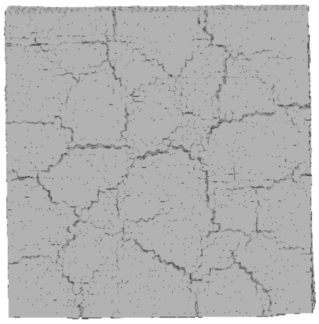
For the aggregate ratio of 15% model, case 3 is chosen, giving 0.001mm initial strain for ASR reactive interfaces, and reached 0.3051% one-dimensional expansion after 20 steps. And for the aggregate ratio of 30% model, case 3 is chosen, giving 0.001mm initial strain for ASR reactive interfaces and reached 0.4223% one-dimensional expansion after 20 steps.

As can be seen in Figure 1.19, at a relatively close global expansion ratio, the cracks are more concentrated with less coarse aggregate ratio case (aggregate 15% here). This indicated that the concentration of location generate expansion could result in the concentration of global cracking distribution. Similar trend is also shown when decreasing the ratio of ASR reactive coarse aggregate ratio, which will be discussed later.

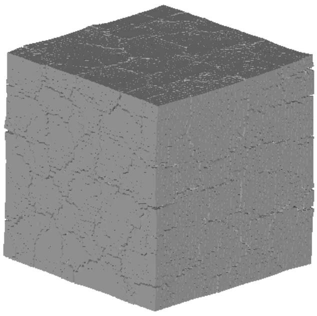
Both of the cases show clear characteristic map cracking which normally observed in ASR expanded concrete structures.



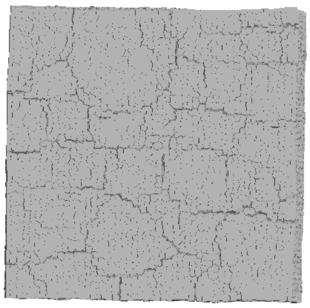
(A) A15 Case 3: 0.3051% Expansion
3D Surface Crack



(B) A15 Case 3: 0.3051% Expansion
3D Surface Cracks (Single Side View)



(C) A30 Case 3: 0.4223% Expansion
3D Surface Crack



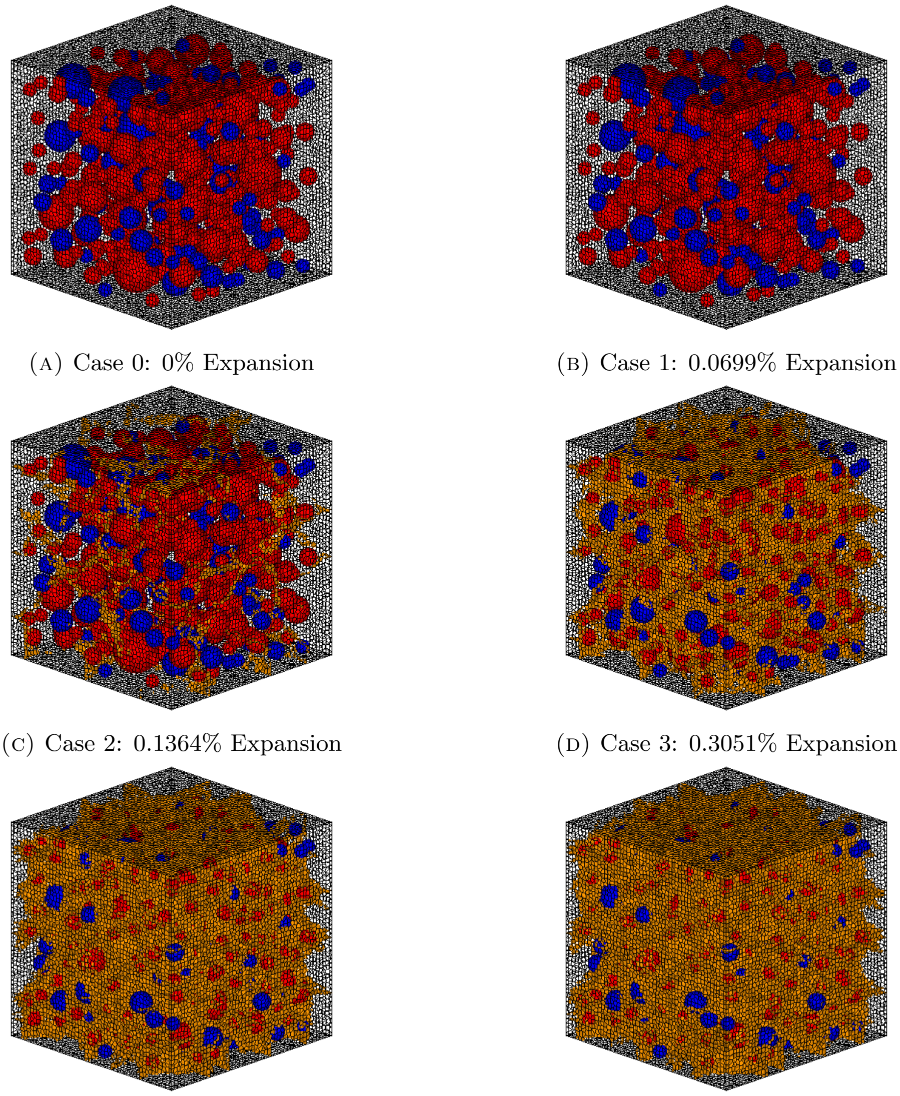
(D) A30 Case 3: 0.4223% Expansion
3D Surface Cracks (Single Side View)

FIGURE 1.17: Comparing Between A15 and A30 3D Surface Cracks (Deformation x 10)

In Figure 1.18, here if compare the inner crack of two cases at a relatively close global expansion ratio, the cracks larger than 0.03mm are generally more with less coarse aggregate ratio case (aggregate 15% here).

If comparing the distribution of cracks summarised by its crack width (Table 1.12), it can be seen that the distribution pattern is relatively close for 15% coarse aggregate case with 0.3051% global expansion and 30% coarse aggregate case with 0.4223% global expansion. The number of cracked faces decrease gradually when increasing the crack width.

However, if compare closer on relatively larger cracks, cracking face number of the case with 15% coarse aggregate is higher. For example, for the number of cracked interfaces larger than 0.003mm, 15% coarse aggregate case is 9.27% higher than 30% coarse aggregate case. And for the number of cracked interfaces larger than 0.01mm,



(A) Case 0: 0% Expansion

(B) Case 1: 0.0699% Expansion

(C) Case 2: 0.1364% Expansion

(D) Case 3: 0.3051% Expansion

(E) Case 4: 0.629% Expansion

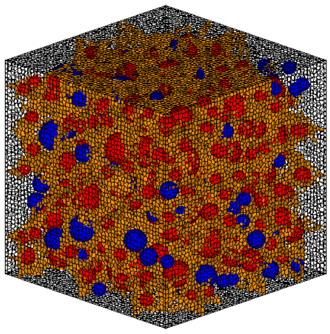
(F) Case 5: 0.9243% Expansion

FIGURE 1.18: 3D Inner Crack Width Larger than 0.03mm

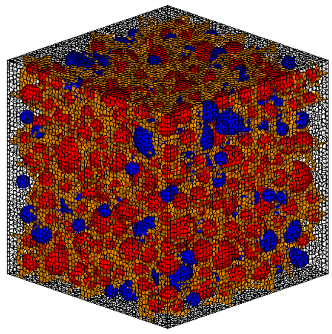
Crack Width [mm]	A15 Case 3 Total Cracked Interfaces	A30 Case 3 Total Cracked Interfaces
0.00000 - 0.00005	363340	316744
0.00005 - 0.00010	303804	286704
0.00010 - 0.00020	263111	263943
0.00020 - 0.00050	220320	234672
0.00050 - 0.00100	163316	183238
0.00100 - 0.00300	117764	131553
0.00300 - 0.01000	45969	42432
0.01000 - 0.03000	696	275
0.03000 - 0.10000	0	0
0.1000+	0	0

TABLE 1.5: Expansion in Each Step for A15P75 Case 3 and A30 P75 Case 3

15% coarse aggregate case is 2.53 times of 30% coarse aggregate case. Those larger cracks having more significant influence when the global cracking patterns are compared and should distribute more when considering the damage on the concrete structure.



(A) A15 Case 3: 0.3051% Expansion 3D Inner Crack



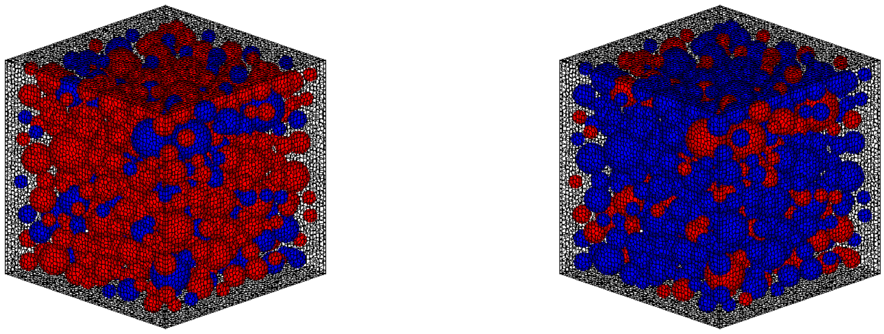
(B) A30 Case 3: 0.4223% Expansion 3D Inner Cracks

FIGURE 1.19: Comparing Between A15 and A30 3D Surface Cracks (Deformation x 10)

1.3.4 Reactive Aggregate Ratio Related to Behavior of Concrete During ASR Expansion

In this section, the relationship between ASR reactive aggregate ratio and behavior during expansion is discussed.

Expansion simulation result of 30% coarse aggregate model is used here, and different ASR reactive ratio (25% of total coarse aggregate and 75% of total coarse aggregate) is given, to analyze how the change in ASR reactive aggregate percentage influence the cracking pattern.



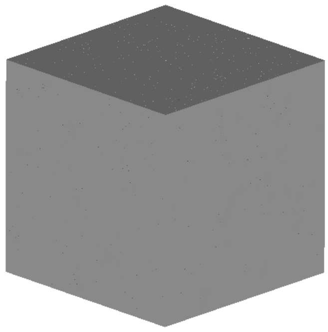
(A) 30% Coarse Aggregate with 75% ASR Reactive Aggregate (B) 30% Coarse Aggregate with 25% ASR Reactive Aggregate

FIGURE 1.20: 25% and 75% ASR Reactive Aggregate Ratio Model

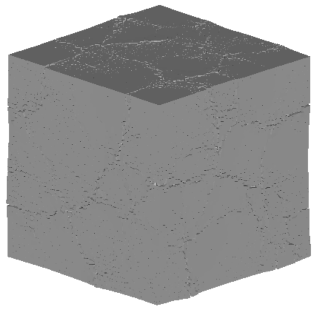
Table 1.6 summarized the giving initial strain in each step and the total step of expansion giving in the two models compared in this section. Relatively larger initial strains are given to the less ASR reactive coarse aggregate cases (25% ASR reactive aggregate cases here) to reach relatively closer global expansion ratio for comparing.

Aggregate Ratio[%]	Reactive Aggregate Ratio[%]	Initial Strain (Each Step)	Expanding Steps	Final Expansion [%]
30	75	0	0	0
30	75	0.0002	20	0.0699
30	75	0.0005	20	0.1936
30	75	0.001	20	0.4223
30	75	0.002	20	0.8832
30	75	0.003	20	1.3224
30	25	0	0	0
30	25	0.001	20	0.1651
30	25	0.002	20	0.3606
30	25	0.004	20	0.7024
30	25	0.006	20	1.0201

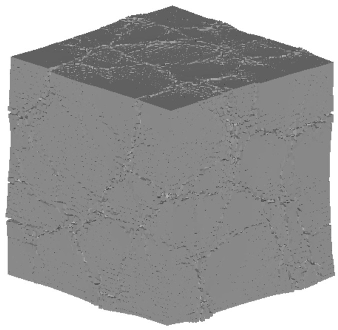
TABLE 1.6: One Dimensional Expansion Ratio in A30P25 and A30P25 ASR Expansion Simulation



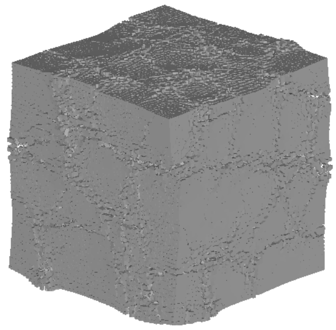
(A) Case 0: 0% Expansion



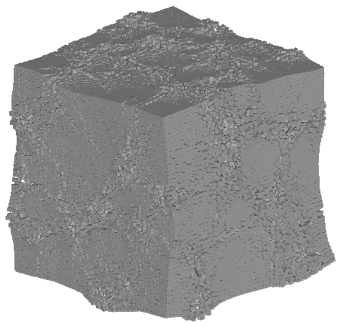
(B) Case 1: 0.1651% Expansion



(C) Case 2: 0.3606% Expansion



(D) Case 3: 0.7024% Expansion



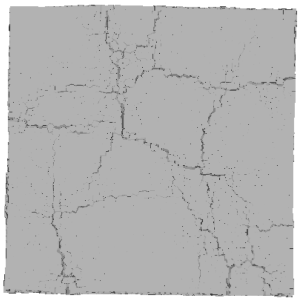
(E) Case 4: 1.0201% Expansion

FIGURE 1.21: 3D Surface Cracks (Deformation x 10)

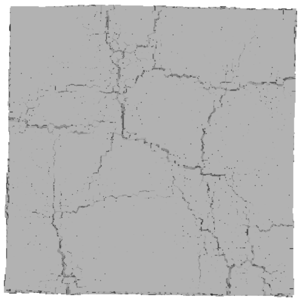
Figure 1.21 and Figure 1.22 show surface crack pattern after ASR expansion of 30% coarse aggregate cases with 25% of the coarse aggregate inside are ASR reactive.

Here 2 cases from 25% ASR reactive coarse aggregate in 30% total coarse aggregate model and 75% ASR reactive coarse aggregate in 30% total coarse aggregate model in relatively close global expansion rate are compared to show the influence of ASR reactive coarse aggregate ratio on cracking pattern.

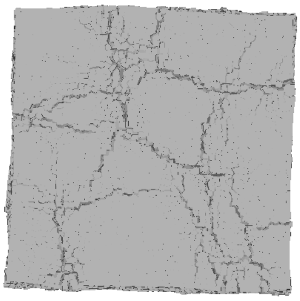
For the reactive aggregate ratio of 25% model, case 2 is chosen, giving 0.002mm initial strain for ASR reactive interfaces in each step, and reached 0.3606% one-dimensional expansion after 20 steps. And for the reactive aggregate ratio of 75% model, case 3 is chosen, giving 0.001mm initial strain for ASR reactive interfaces and reached 0.4223% one-dimensional expansion after 20 steps.



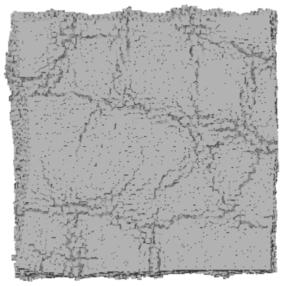
(A) Case 0: 0% Expansion



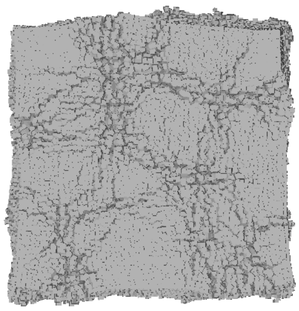
(B) Case 1: 0.1651% Expansion



(C) Case 2: 0.3606% Expansion



(D) Case 3: 0.7024% Expansion



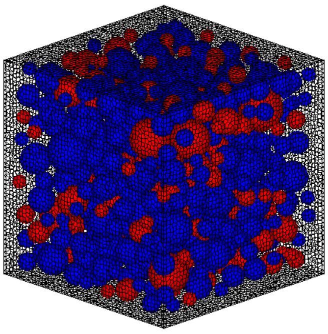
(E) Case 4: 1.0201% Expansion

Figure 1.22: 3D Surface Cracks (Single Side View, Deformation x 10)

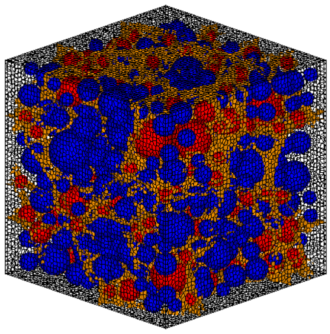
As can be seen in Figure 1.24, at a relatively close global expansion ratio, the cracks are more concentrated with less reactive coarse aggregate ratio case (reactive aggregate ratio of 25% cases here). This indicated that the concentration of location generate expansion could result in the concentration of global cracking distribution, which consists with the previous cases when the total aggregate percentage is decreased.

Still, both of the cases show clear characteristic map cracking which observed in typical ASR expanded concrete structures.

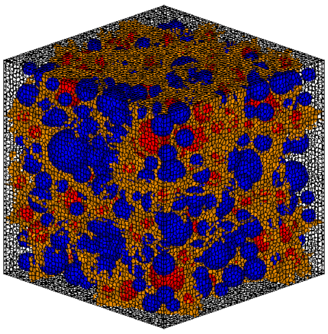
And from Figure 1.25, the inner cracking distribution of 2 cases are also compared. It can be seen that the case with less reactive coarse aggregate ratio (15% ASR reactive aggregate) is having less distributed cracks (larger than 0.03mm).



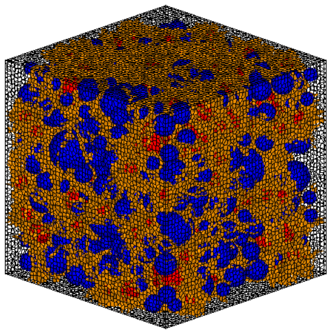
(A) Case 0: 0% Expansion



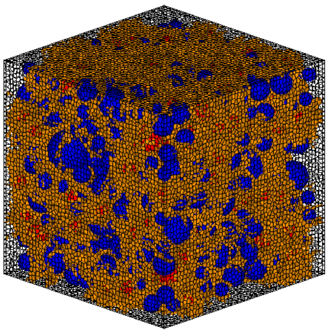
(B) Case 1: 0.1651% Expansion



(C) Case 2: 0.3606% Expansion



(D) Case 3: 0.7024% Expansion

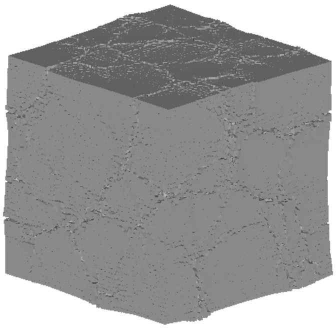


(E) Case 4: 1.0201% Expansion

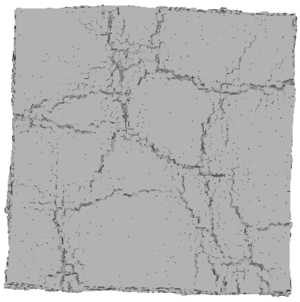
FIGURE 1.23: 3D Inner Cracks

Crack Width [mm]	A30P25 Case 2 Total Cracked Interfaces	A30P75 Case 3 Total Cracked Interfaces
0.00000 - 0.00005	327828	316744
0.00005 - 0.00010	280821	286704
0.00010 - 0.00020	256125	263943
0.00020 - 0.00050	229235	234672
0.00050 - 0.00100	189533	183238
0.00100 - 0.00300	154639	131553
0.00300 - 0.01000	85126	42432
0.01000 - 0.03000	6584	275
0.03000 - 0.10000	0	0
0.1000+	0	0

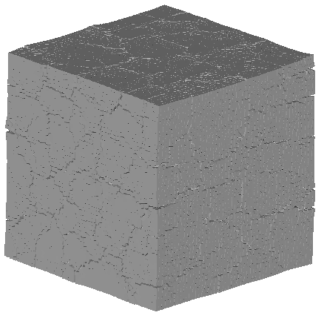
TABLE 1.7: Comparing Between A30P25 and A30P25 3D Surface Cracks



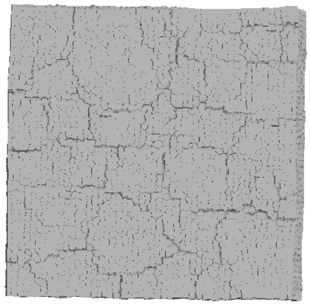
(A) A30P25 Case 2: 0.3606% Expansion
3D Surface Crack



(B) A30P25 Case 2: 0.3606% Expansion
3D Surface Cracks (Single Side View)

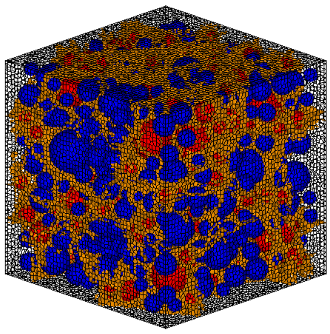


(C) A30P75 Case 3: 0.4223% Expansion
3D Surface Crack

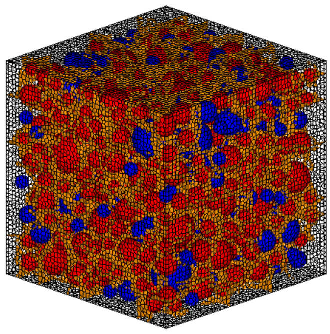


(D) A30P75 Case 3: 0.4223% Expansion
3D Surface Cracks (Single Side View)

FIGURE 1.24: Comparing Between A30P25 and A30P75 3D Surface Cracks (Deformation x 10)



(A) A30P25 Case 2: 0.3606% Expansion
3D Inner Crack



(B) A30P75 Case 3: 0.4223% Expansion
3D Inner Crack

FIGURE 1.25: Comparing Between A30P25 and A30P75 3D Surface Cracks (Deformation x 10)

When numerically comparing their crack distribution summarised by its crack width (Table 1.7), it can be seen that cracking face number of larger cracks the case with 25% ASR reactive coarse aggregate is significantly higher, even when the global expansion ratio in 25% ASR reactive coarse aggregate is slightly smaller than 75% ASR reactive coarse aggregate case.

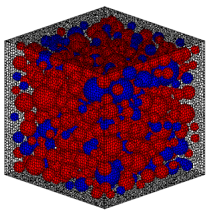
For the number of cracked interfaces larger than 0.003mm, 25% ASR reactive coarse aggregate case is 2.15 times of 75% ASR reactive coarse aggregate case. And for the number of cracked interfaces larger than 0.01mm, 25% ASR reactive coarse aggregate case is 23.94 times of 75% ASR reactive coarse aggregate case.

This significant difference in crack distribution indicates consisit with the global cracking patterns, suggest severe damage when considering the deterioration of the concrete structure.

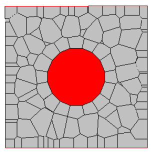
1.4 Cracking Pattern caused by Pure DEF Expansion

1.4.1 DEF Expansion Simulation of Single Aggregate Case

In this section, similar as in ASR cases, simulation of DEF expansion on 10x10x10mm size model with only single aggregate in center of it is presented.



(A) 3D View



(B) Cross Section View

FIGURE 1.26: Single Aggregate Case in Size 10x10x10mm (Deformation x 10)

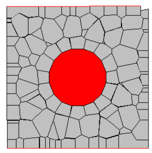
The expanse is generated at the location of interfaces between mortar and mortar elements, to introduce the expansion, as mentioned in chapter 2.

As the model is small in size, and it is a representation of the expansion in part of the whole structure in theoretically, uniform expansion is applied here.

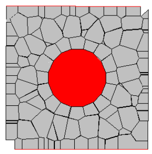
0.0003 initial strain is introduced in each step at the interfaces between the paste and paste elements. Totally 20 steps of expansion are done.

From the Figure 1.27, we can see that step by step with initial stain introducing into the model, distance appears between aggregate and the surrounding element at first, meanwhile the distance between paste elements open gradually as we increase the step of expansion.

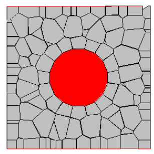
As the paste apart from aggregate in the center, there is no compressive or tension stress appearing in the aggregate.



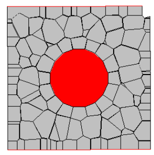
(A) Step 1



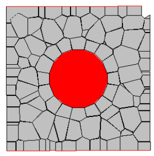
(B) Step 2



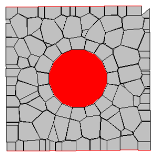
(C) Step 3



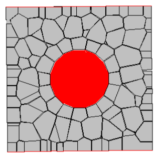
(D) Step 4



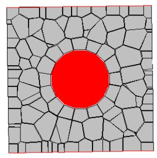
(E) Step 5



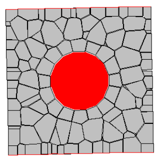
(F) Step 6



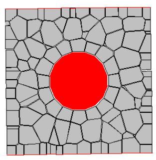
(G) Step 7



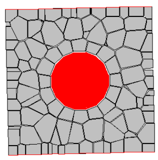
(H) Step 4



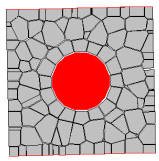
(I) Step 9



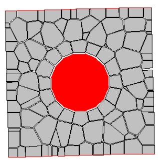
(J) Step 10



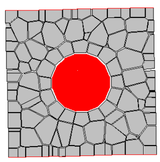
(K) Step 11



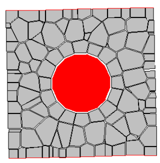
(L) Step 12



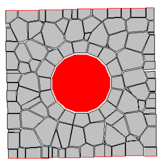
(M) Step 13



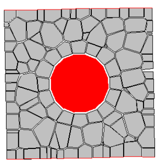
(N) Step 14



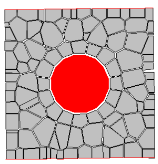
(O) Step 15



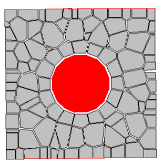
(P) Step 16



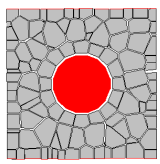
(Q) Step 17



(R) Step 18



(S) Step 19



(T) Step 20

FIGURE 1.27: Internal Stress in Each Step for DEF 10x10x10mm Case (Deformation x 10)

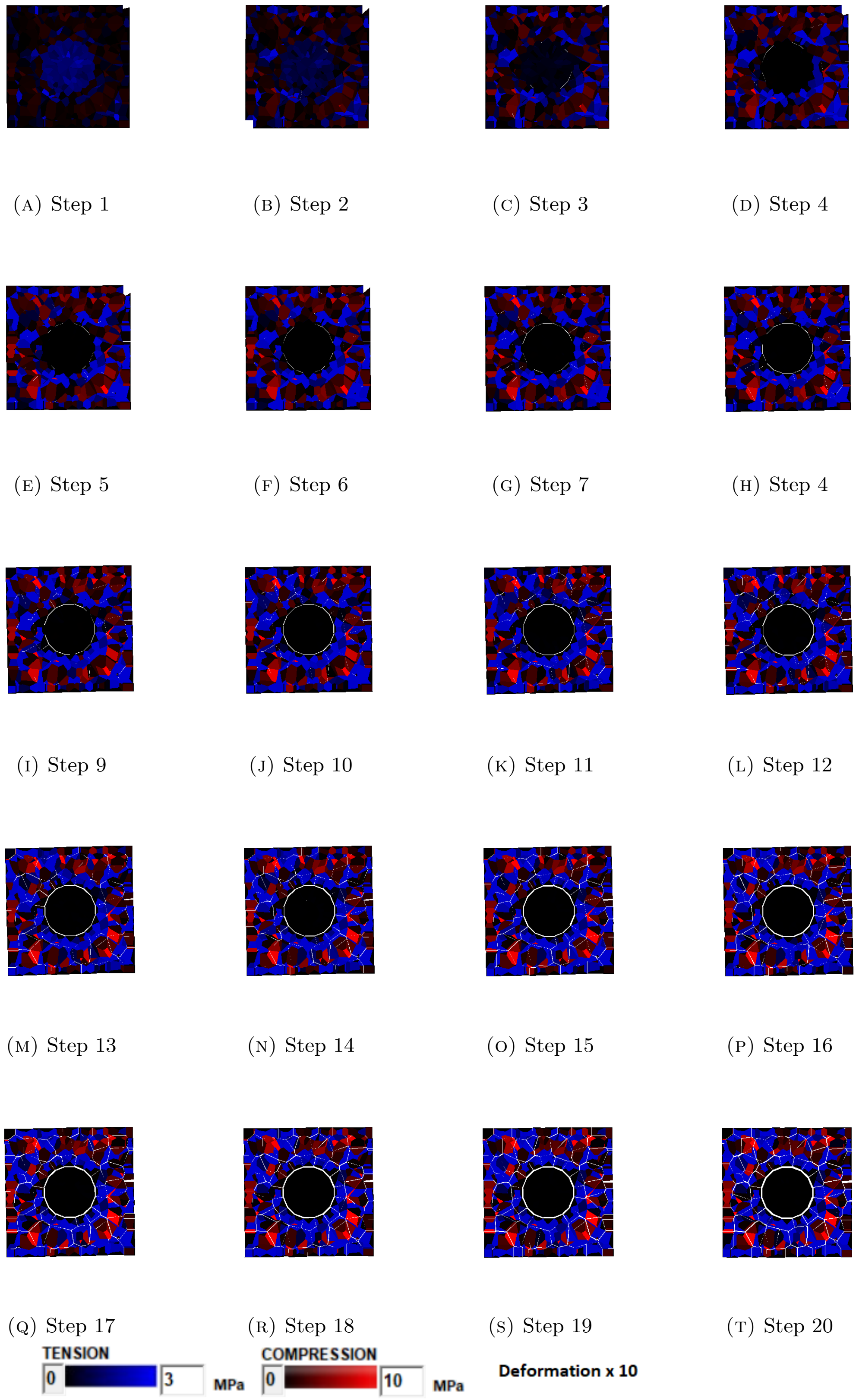
Not like the case of ASR, the DEF expansion here have relatively uniformed opening in all paste parts.

The total volume of this small model is increasing step by step, while until the step 20 the model expanded 0.6098% one-dimensionally.

Also, the Inner Stress condition for each step is collected, and shown in Figure 1.28.

As shown in the inner stress condition, at eh beginning of the expansion, the aggregate is under tensile stress and paste parts surrounding is under compression. Since the initial strain is given to the paste, with the increasing of initial strain by each step, the compressive stress accumulates in the paste part. While for the aggregate, after gap developed between aggregate and paste around it, the aggregate is not suffering from tension or compression.

This very small size simple example shows that, same as ASR case, logically our method of adding initial strain to generate DEF expansion should work in the way we assumed.



(A) Step 1 (B) Step 2 (C) Step 3 (D) Step 4

(E) Step 5 (F) Step 6 (G) Step 7 (H) Step 4

(I) Step 9 (J) Step 10 (K) Step 11 (L) Step 12

(M) Step 13 (N) Step 14 (O) Step 15 (P) Step 16

(Q) Step 17 (R) Step 18 (S) Step 19 (T) Step 20

FIGURE 1.28: Internal Stress in Each Step for DEF 10x10x10mm Case (Deformation x 10)

1.5 Cracking Pattern caused by Pure DEF Expansion

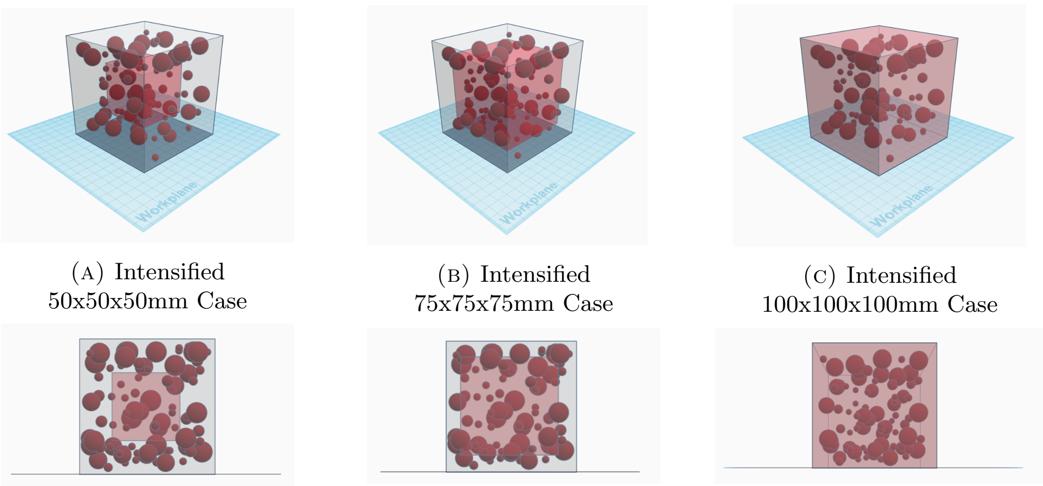
1.5.1 Single DEF Expansion Simulation

In this section, the relationship between DEF intensified part range and concrete behavior during DEF expansion is simulated. The expanse is generated at the location of interfaces between paste element, to introduce the DEF expansion, as introduced in chapter 2.

For DEF expansion is highly related to the curing temperature concrete experienced, it is reasonable to considerate the inner part of the concrete structure should present more severe expansion comparing with outer part, due to its higher maximum experienced temperature during steam curing.

For surrounding part of the model, cases of non-expansion and gradually decreasing expansion are considered.

In this section, 100x100x100mm model is using. For comparison, 3 different cases are simulated, which are intensified 50x50x50mm at the center of the model, intensified 75x75x75mm at the center of the model, and intensified all part of the model (100x100x100mm).



(A) Intensified 50x50x50mm Case

(B) Intensified 75x75x75mm Case

(C) Intensified 100x100x100mm Case

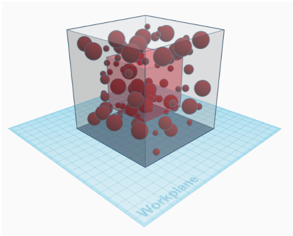
(D) Intensified 50x50x50mm Case Cross Section

(E) Intensified 75x75x75mm Case Cross Section

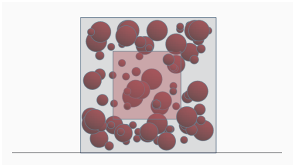
(F) Intensified 100x100x100mm Case Cross Section

FIGURE 1.29: DEF intensified part range

This single example case showing here as an example has been choosing here use the model in the dimension of 100x100x100mm, with 30% aggregate, of which center 50x50x50mm have intensified DEF reactive, and the expanding giving to the model gradually decrease to 0 in the surrounded part.



(A) Intensified
50x50x50mm Case



(B) Intensified
50x50x50mm Case
Cross Section

FIGURE 1.30: 50x50x50mm DEF intensified part range

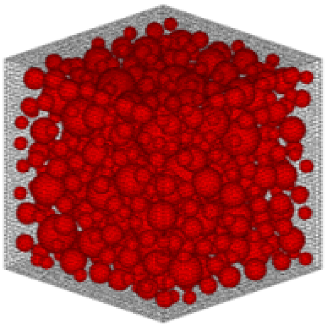


FIGURE 1.31: 30% Coarse Aggregate

Table. Aggregate consistent(if we have it)

To simulate DEF expansion, an initial strain of 0.0004mm is given in intensified DEF expanding area in each step, and the initial strain gradually decrease to 0 for surrounded parts, for totally 20 steps expansion.

Step	Expansion	Step	Expansion
1	0.000235	11	0.003061
2	0.000506	12	0.003355
3	0.000776	13	0.003650
4	0.001051	14	0.003949
5	0.001329	15	0.004249
6	0.001615	16	0.004555
7	0.001900	17	0.004865
8	0.002188	18	0.005175
9	0.002478	19	0.005487
10	0.002768	20	0.005795

TABLE 1.8: Expansion in Each Step for A30 Case 3

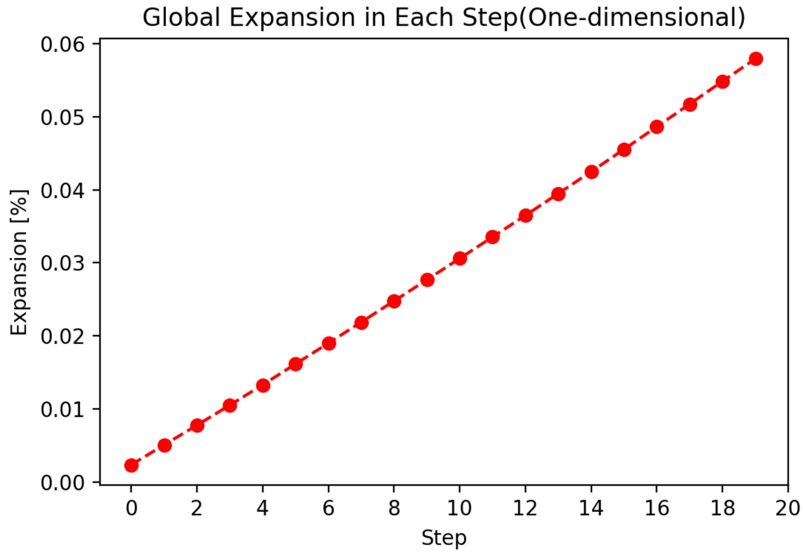


FIGURE 1.32: Global Expansion vs. Step

With the increasing of initial strain giving, the global expansion also gradually increasing. After 20 steps of DEF expansion, the model here reached 0.5795% expansion(one-dimensionally). Characteristic DEF map cracking pattern can be seen on the surface of the expanded concrete modelin Figure 1.33.

In Figure ??, the inner distribution of cracked interface with width greater than 0.03mm is presented. It can be seen that the cracks are located with very clear patterns, concentrated in the inner part of the model. This inner cracking distribution pattern is very different with the cases ASR expansion.

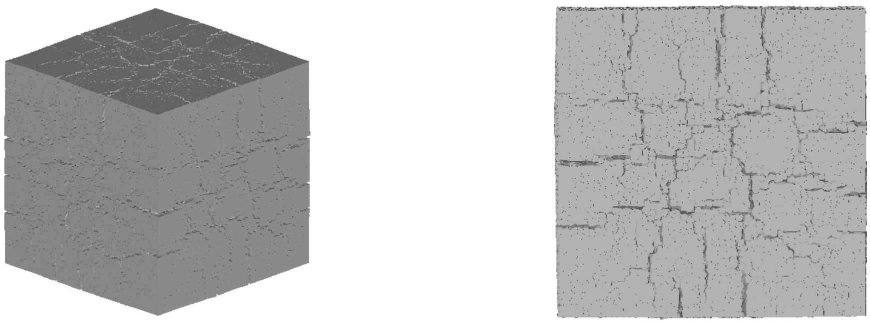


FIGURE 1.33: 3D Surface Cracks, 0.4223% Expansion (Deformation x 10)

As can be seen in Figure 1.35 the compressive stress (in red color) first concentrated in the part where initial strain is intensified given, and from step 1 to 20, unbalanced force penetrated in the concrete model, crack generated gradually around the aggregate and the surrounding part of the model.

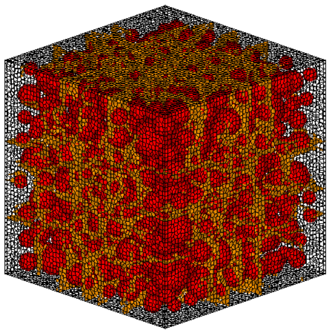
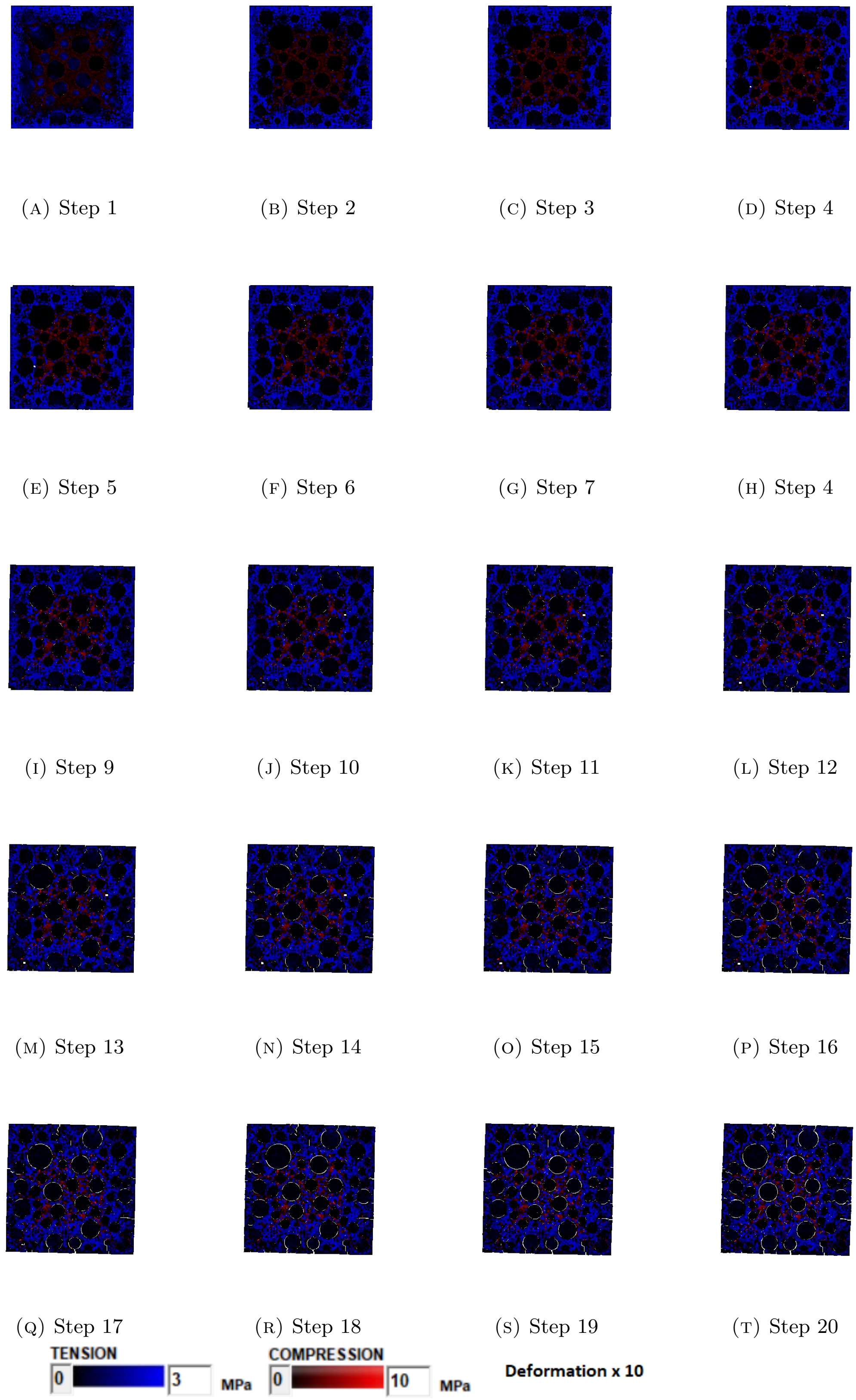


FIGURE 1.34: 3D Inner Cracks, 0.4223% Expansion

Same as previous in ASR expansion simulation, cracked interfaces are summarised in different crack width scale, shown in Table 1.9. The maximum crack width, in this case, is in range of 0.01-0.03mm, while most of the cracks still under 0.001mm. The number of cracked interfaces gradually decreases with the increase of crack width.

Crack Width [mm]	Total Cracked Interfaces
0.00000 - 0.00005	367538
0.00005 - 0.00010	328471
0.00010 - 0.00020	294472
0.00020 - 0.00050	251035
0.00050 - 0.00100	186058
0.00100 - 0.00300	133854
0.00300 - 0.01000	57421
0.01000 - 0.03000	1736
0.03000 - 0.10000	0
0.1000+	0

TABLE 1.9: Expansion in Each Step for A30 X0C Case 3



(A) Step 1 (B) Step 2 (C) Step 3 (D) Step 4

(E) Step 5 (F) Step 6 (G) Step 7 (H) Step 4

(I) Step 9 (J) Step 10 (K) Step 11 (L) Step 12

(M) Step 13 (N) Step 14 (O) Step 15 (P) Step 16

(Q) Step 17 (R) Step 18 (S) Step 19 (T) Step 20

FIGURE 1.35: Internal Stress in Each Step for A30 X0C Case 3 (Deformation x 10)

1.5.2 Expansion Ratio Related to Behavior of Concrete During DEF Expansion

In this section, the relationship between given initial strain, final expansion and behavior during expansion is discussed.

Model in size of 100x100x100mm is in used, with 30% Aggregate, and 25% area have intensified DEF reaction, while the expanding giving to the model gradually decrease to 0 in the surrounded part.

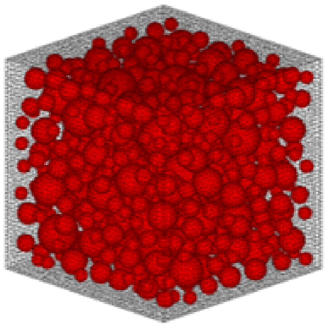


FIGURE 1.36: 30% Coarse Aggregate

Expansion is carried out with initial strain given in each step for intensified zone various from 0 to 0.0006mm. Initial strain given to the surrounding part of paste gradually decreasing to 0. Total expansion step are set as 20 steps same for all cases. From the Table 1.10 can be seen that with the increasing of giving initial strain in each step, the global expansion reached in step 20 also increased.

Aggregate Ratio[%]	Intensified DEF Reacting Area[%]	Initial Strain (Intensified Area, Each Step)	Expanding Steps	Final Expansion [%]
30	25	0	0	0
30	25	0.0001	20	0.1379
30	25	0.0002	20	0.2873
30	25	0.0004	20	0.5795
30	25	0.0006	20	0.8789

TABLE 1.10: One Dimensional Expansion Ratio in Single DEF Model Simulation

As shown in Figure 1.38 and Figure 1.39, it is clear that with the increase of global expansion ratio, the cracking can be seen on the surface of concrete model become much significant. However, the map cracking pattern does not change much comparing the expanded models in different expansion ratio.

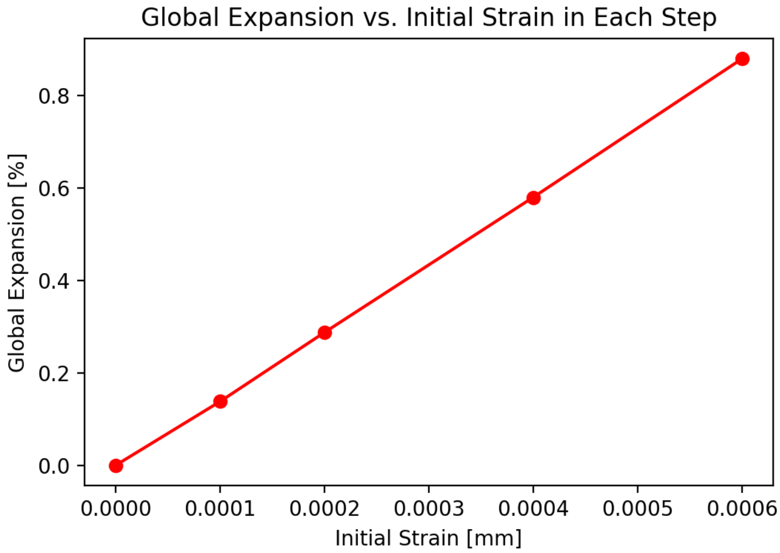


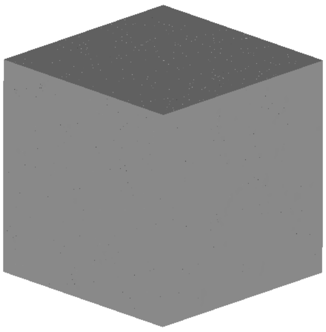
FIGURE 1.37: Global Expansion vs. Step

And in Figure 1.40, the internal cracking distribution in different global expansion cases are presented. It can be seen that the cross pattern of internal cracks gradually generate and penetrated, but still the pattern of its distribution dose not change in much. At small ratio of global exoansion, cracks are concentrated in the center of each surface, then penetrated to larger range with increasing of global expansion ratio.

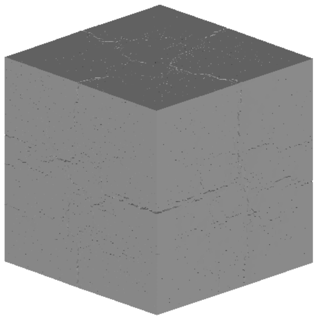
This indicated that our simulation can still predict the map cracking behavior for DEF expansion in different deterioration levels.

In Figure 1.41, the internal stress distribution in some middle step and last expansion step are shown. By increasing the initial strain giving to present DEF expansion in each step, the expansion developed more rapidly and more cracks generated especially on the outside part of concrete sturcture. This result is consistent with the 3D cracking pattern presented earlier in this section, where cracks are generated in the surrounding part of the model.

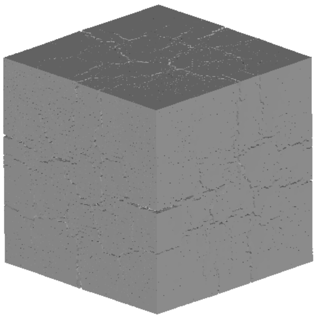
This pattern of crack development is very different from ASR cases, and may suggests deterioration caused by DEF may not suffering severe inner structually damage inside as it looks from the surface.



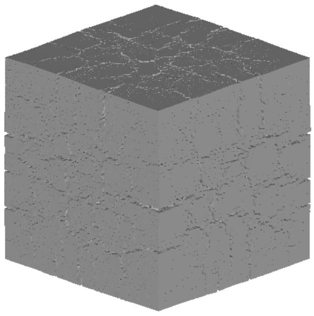
(A) Case 0: 0% Expansion



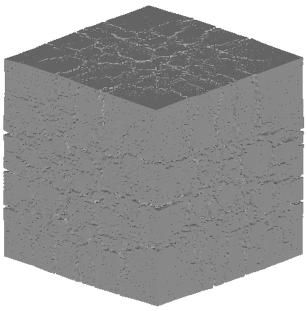
(B) Case 1: 0.1379% Expansion



(C) Case 2: 0.2873% Expansion

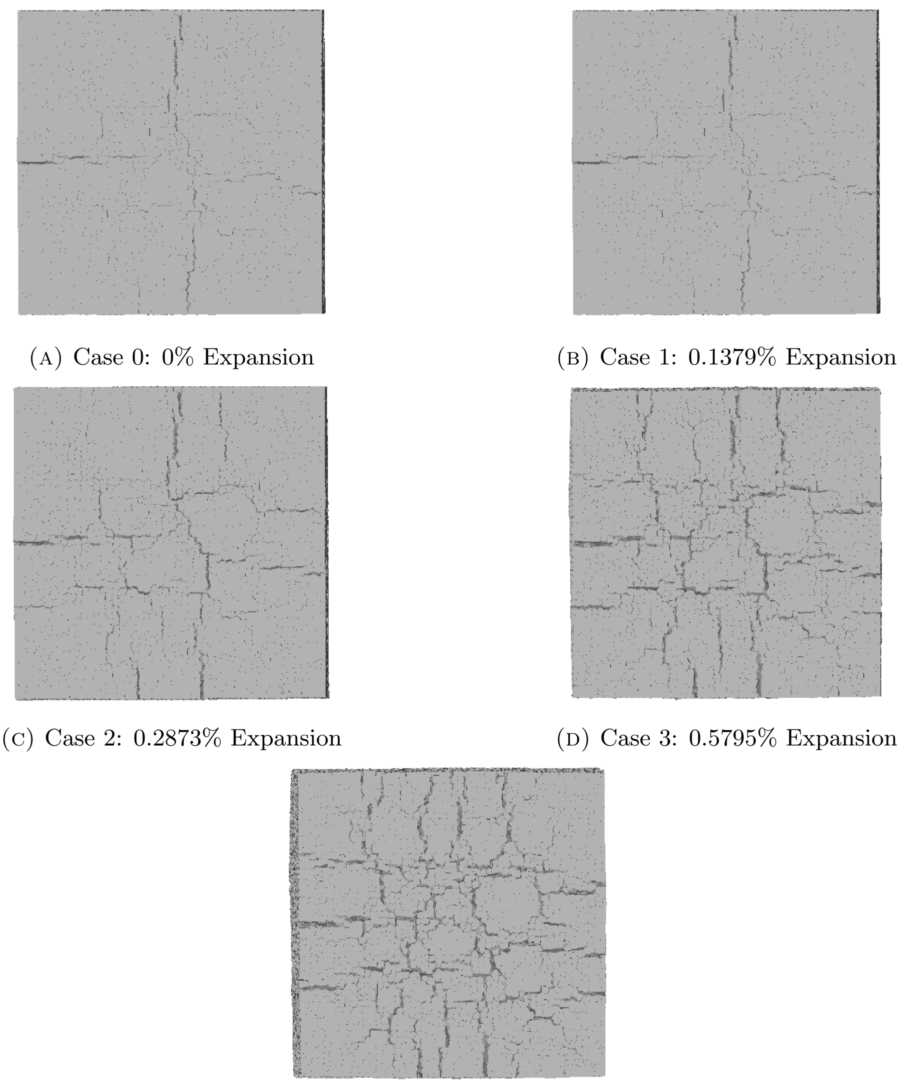


(D) Case 3: 0.5795% Expansion



(E) Case 4: 0.8789% Expansion

FIGURE 1.38: 3D Surface Cracks (Deformation x 10)



(A) Case 0: 0% Expansion

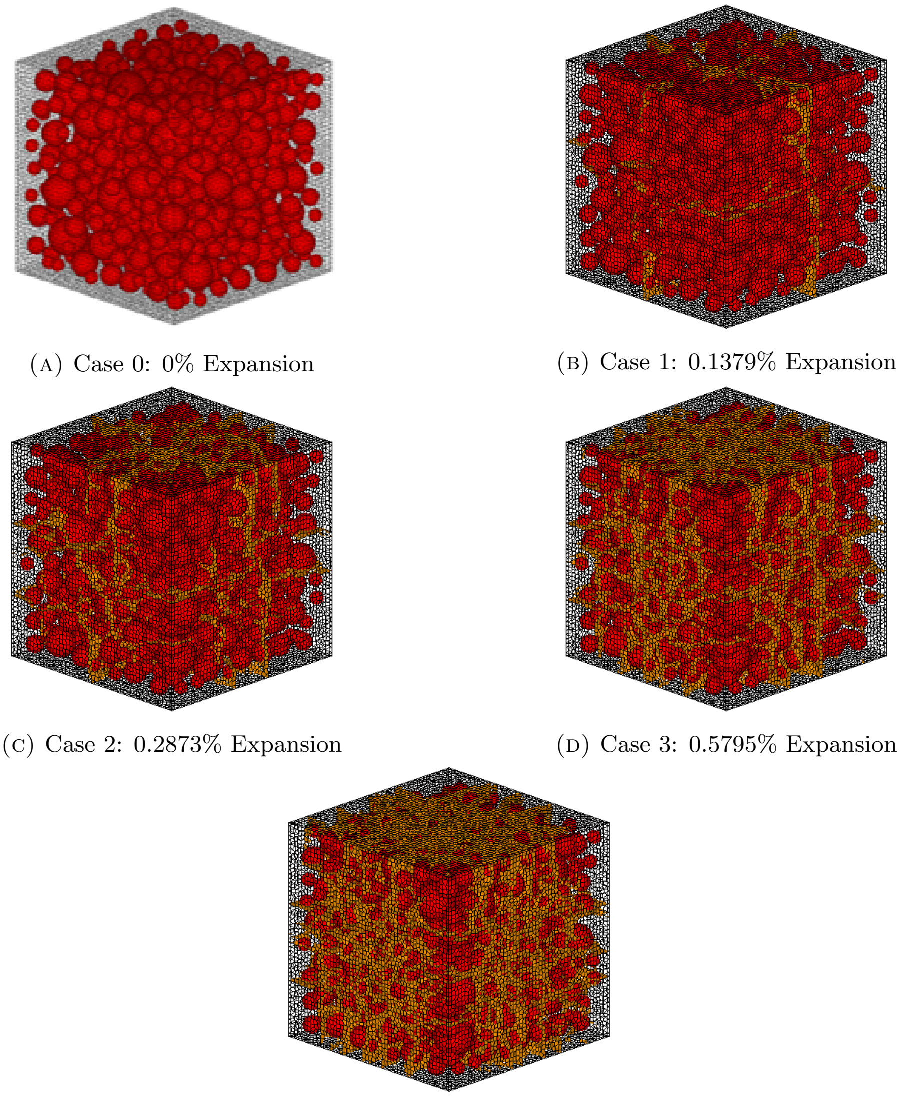
(B) Case 1: 0.1379% Expansion

(C) Case 2: 0.2873% Expansion

(D) Case 3: 0.5795% Expansion

(E) Case 4: 0.8789% Expansion

FIGURE 1.39: 3D Surface Cracks (Single Side View, Deformation x 10)



(A) Case 0: 0% Expansion

(B) Case 1: 0.1379% Expansion

(C) Case 2: 0.2873% Expansion

(D) Case 3: 0.5795% Expansion

(E) Case 4: 0.8789% Expansion

FIGURE 1.40: 3D Inner Cracks Larger than 0.03mm

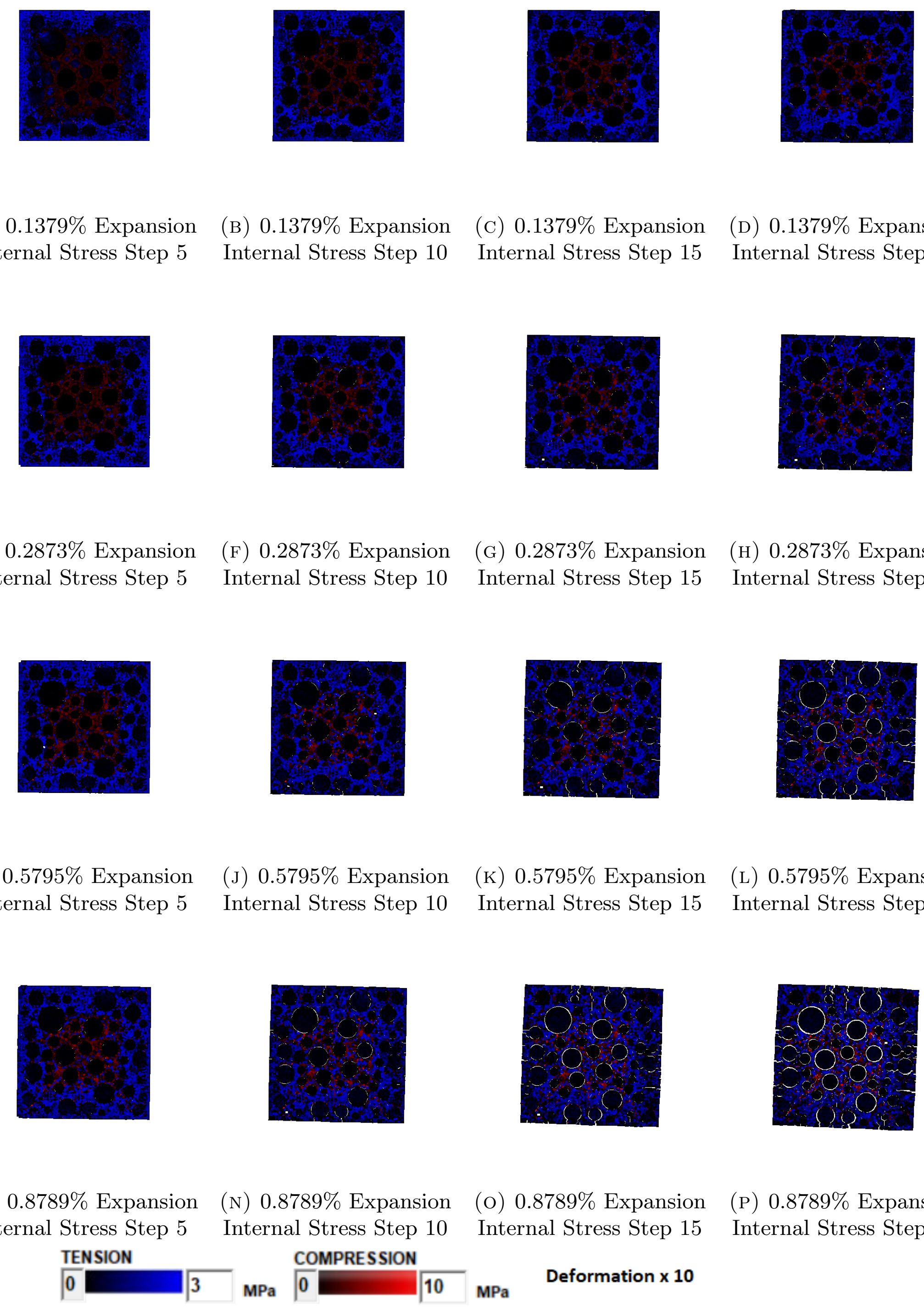


FIGURE 1.41: Generation of Internal Stress and Inner Cracks for DEF Expansion to Step 20(Final Expansion Step, Deformation x 10)

1.5.3 Aggregate Ratio Related to Behavior of Concrete During DEF Expansion

In this section, the relationship between aggregate ratio and behavior during expansion is discussed.

Expansion simulation result between 15% coarse aggregate model and 30% coarse aggregate model is compared here to analysis how the change in aggregate percentage influence the cracking pattern in different expansion ratio.

(A) 15% Coarse Aggregate

(B) 30% Coarse Aggregate

FIGURE 1.42: Coarse Aggregate Percentage

From Table 1.11 can be seen that with same expansion step and same initial strain given in each step, the global expansion of with less coarse aggregate (A15 cases here) is higher than less coarse aggregate cases (A30 cases here). As coarse aggregate ratio increased, DEF reactive interfaces decrease, which suggested the reason for achieving smaller global expansion in higher coarse aggregate cases.

Initial Strain (Each Step)	Expanding Steps	A15 Final Expansion	A30 Final Expansion[%]
0	0	0	0
0.001	20	0.1645	0.1379
0.002	20	0.3413	0.2873
0.004	20	0.6631	0.5795
0.006	20	0.9587	0.8785

TABLE 1.11: One Dimensional Expansion Ratio in Single DEF Model Simulation

Figure 1.44 and Figure **??** show surface crack pattern after DEF expansion of 15% coarse aggregate cases.

Here 2 cases from 15% coarse aggregate model and 30% coarse aggregate model in relatively close global expansion rate are compared to show the influence of coarse aggregate ratio on cracking pattern.

For the aggregate ratio of 15% model, case 3 is chosen, giving 0.0004mm initial strain for intensified DEF reactive interfaces, and reached 0.6631% one-dimensional expansion

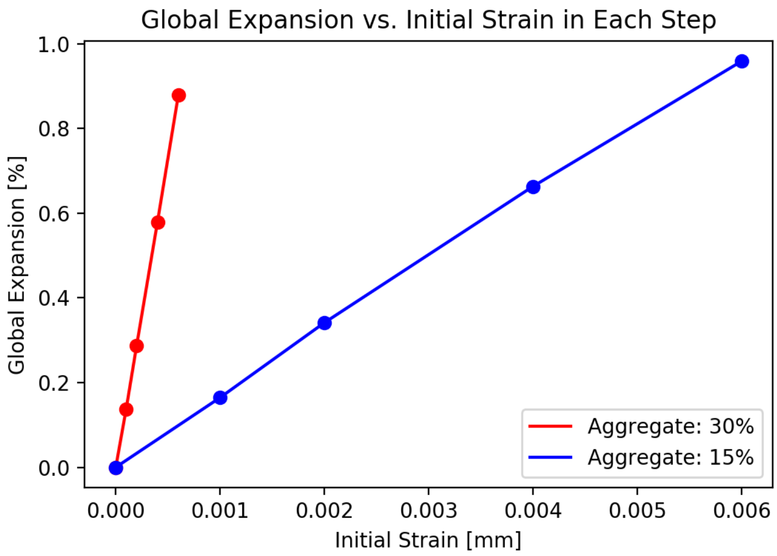
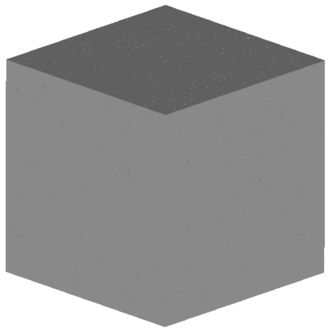


FIGURE 1.43: Global Expansion vs. Step

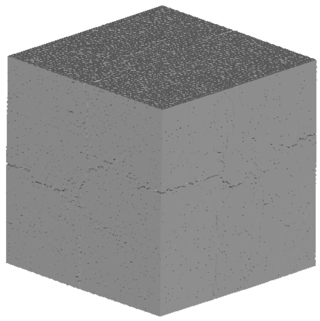
after 20 steps. And for the aggregate ratio of 30% model, case 3 is chosen, giving 0.004mm initial strain for DEF reactive interfaces and reached 0.5795% one-dimensional expansion after 20 steps.

If plot the global expansion with initial strain given in each step to simulate DEF expansion, it can be seen that model with higher percentage of aggregate reach higher global expansion in the same initial strain giving comparing to to lower aggregate content one.

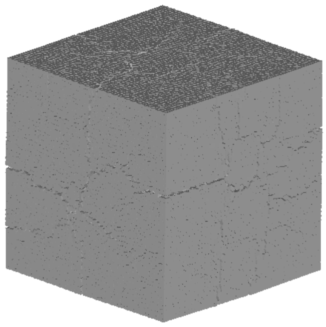
This may caused by more complicated interaction between expanded pastes and aggregate.



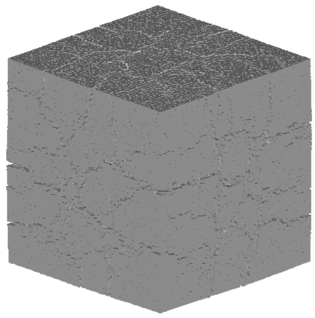
(A) Case 0: 0% Expansion



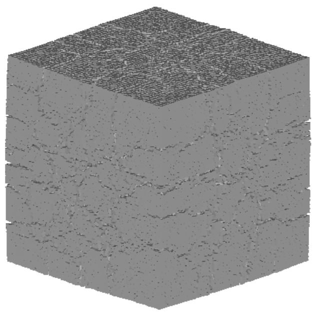
(B) Case 1: 0.1645% Expansion



(C) Case 2: 0.3413% Expansion



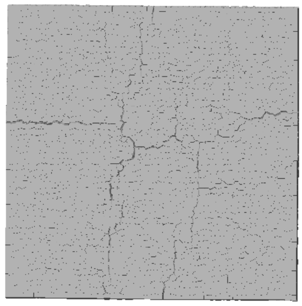
(D) Case 3: 0.6631% Expansion



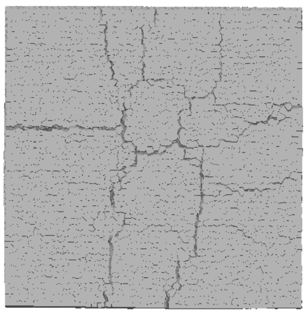
(E) Case 4: 0.9587% Expansion

FIGURE 1.44: 3D Surface Cracks

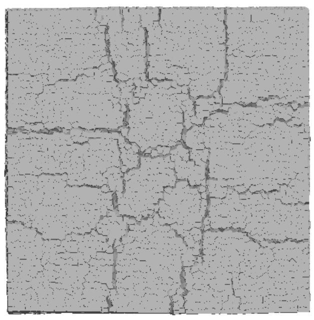
(A) Case 0: 0% Expansion



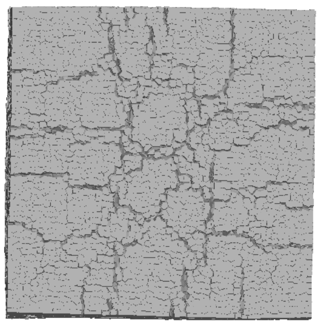
(B) Case 1: 0.1645% Expansion



(C) Case 2: 0.3413% Expansion

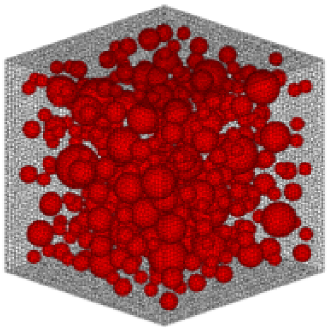


(D) Case 3: 0.6631% Expansion

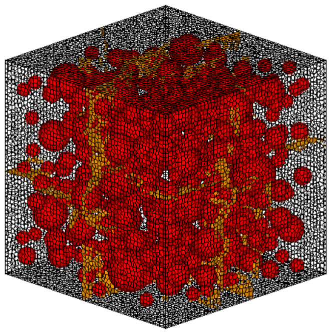


(E) Case 4: 0.9587% Expansion

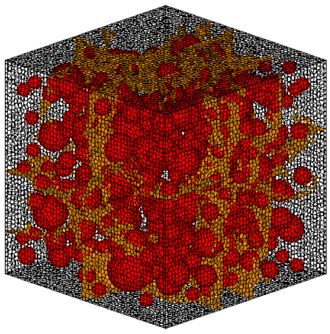
FIGURE 1.45: 3D Surface Cracks (Single Side View)



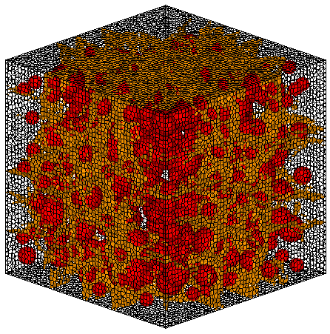
(A) Case 0: 0% Expansion



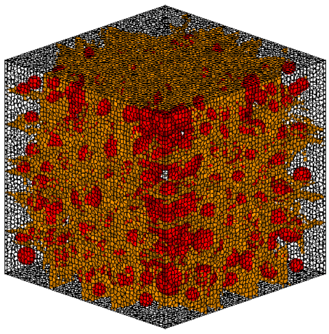
(B) Case 1: 0.1645% Expansion



(C) Case 2: 0.3413% Expansion

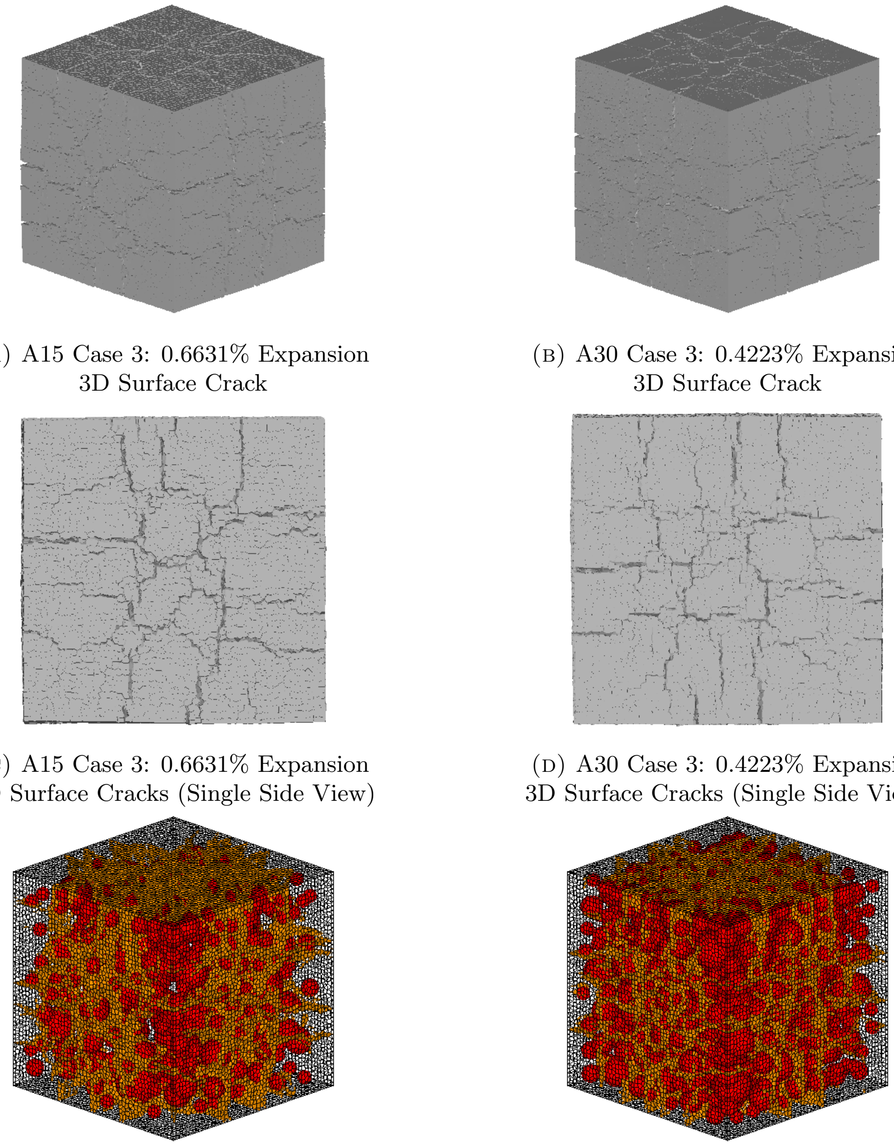


(D) Case 3: 0.6631% Expansion



(E) Case 4: 0.9587% Expansion

FIGURE 1.46: 3D Inner Cracks Larger than 0.03mm



(A) A15 Case 3: 0.6631% Expansion 3D Surface Crack

(B) A30 Case 3: 0.4223% Expansion 3D Surface Crack

(C) A15 Case 3: 0.6631% Expansion 3D Surface Cracks (Single Side View)

(D) A30 Case 3: 0.4223% Expansion 3D Surface Cracks (Single Side View)

(E) A15 Case 3: 0.6631% Expansion 3D Surface Crack

(F) A30 Case 3: 0.4223% Expansion 3D Surface Crack

FIGURE 1.47: Comparing Between A15 and A30 3D Cracks

As can be seen in Figure 1.47, at a relatively close global expansion ratio, the crack pattern on the surface of the expanded model are also very similar. This indicated that aggregate ratio does not influence the behavior of DEF expansion so obviously as it does in ASR cases.

Clear characteristic map cracking which normally observed in DEF expanded concrete structures is presented in both cases.

Also, in Figure 1.47, the inner crack distribution of 2 cases are compared. Though it is difficult to tell the difference by naked eyes, if comparing the distribution of cracks

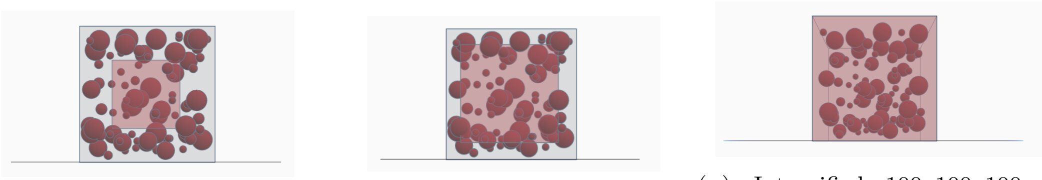
Crack Width [mm]	A15 Case 3 Total Cracked Interfaces	A30 Case 3 Total Cracked Interfaces
0.00000 - 0.00005	396456	367538
0.00005 - 0.00010	344516	328471
0.00010 - 0.00020	294996	294472
0.00020 - 0.00050	231816	251035
0.00050 - 0.00100	151693	186058
0.00100 - 0.00300	105939	133854
0.00300 - 0.01000	3983	57421
0.01000 - 0.03000	696	1736
0.03000 - 0.10000	0	0
0.1000+	0	0

Table 1.12: Expansion in Each Step for A15P75 Case 3 and A30 P75 Case 3

numerically summarised by its crack width (Table 1.12), it can be seen that the distribution pattern is very close for 15% coarse aggregate case with 0.6631% global expansion and 30% coarse aggregate case with 0.5795% global expansion. The number of cracked faces decrease gradually when increasing the crack width.

However, if compare closer on relatively larger cracks, cracking face number of the case with 30% coarse aggregate is higher. For example, for the number of cracked interfaces larger than 0.003mm, 15% coarse aggregate case is 12.64 times of 30% coarse aggregate case. And for the number of cracked interfaces larger than 0.01mm, 30% coarse aggregate case is 2.49 times of 15% coarse aggregate case. Those larger cracks having more significant influence when the global cracking patterns are compared and should distribute more when considering the damage on the concrete structure. Though it is difficult to distinguish by naked eye, the cracking pattern in 30% coarse aggregate case is confirmed to be more concenreate with more large cracks in scale.

1.5.4 Expansion Intensified Part Range Related to Behavior of Concrete During DEF Expansion



(A) Intensified 50x50x50mm Case Cross Section (B) Intensified 75x75x75mm Case Cross Section (C) Intensified 100x100x100mm Case Cross Section

FIGURE 1.48: DEF intensified part range

In this section, DEF expansion simulation result of intensified center 75x75x75mm and uniformly expansion for all part (intensified center 100x100x100mm) is presented.

1.5.4.1 Expansion Intensified 75x75x75mm at Center of Model

Initial Strain (Each Step)	Expanding Steps	Final Expansion[%]
0	0	0
0.001	20	0.1671
0.002	20	0.3380
0.003	20	0.5118
0.005	20	0.8577

TABLE 1.13: One Dimensional Expansion Ratio in Expansion Intensified 75x75x75mm at Center of Model DEF Model Simulation

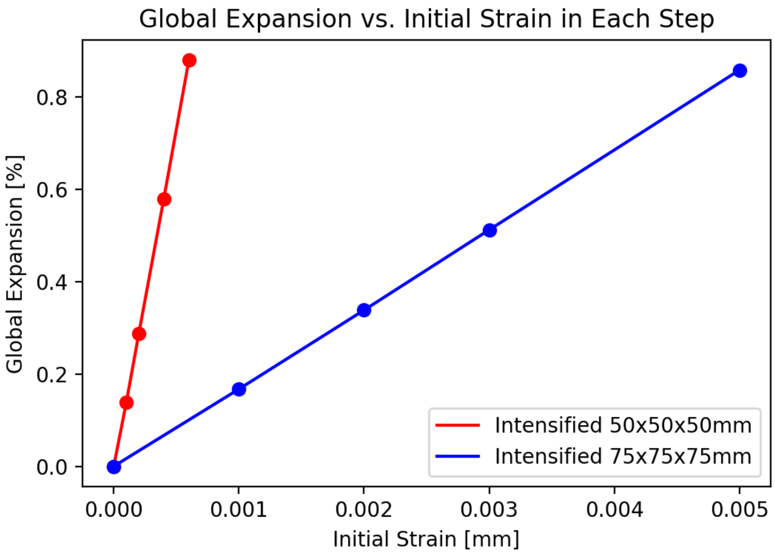
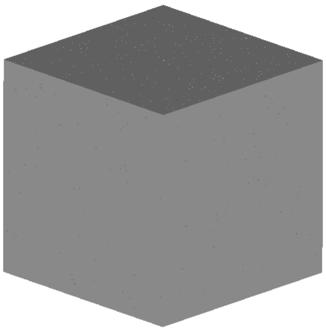
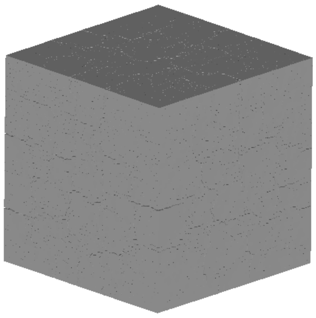


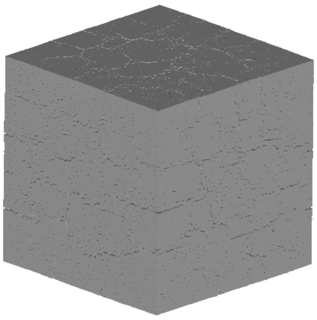
FIGURE 1.49: Global Expansion vs. Step



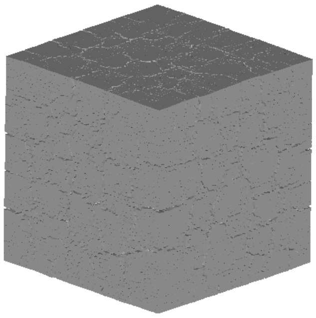
(A) Case 0: 0% Expansion



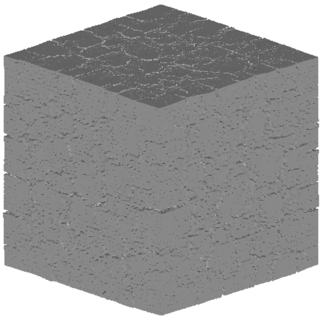
(B) Case 1: 0.1671% Expansion



(C) Case 2: 0.3380% Expansion



(D) Case 3: 0.5118% Expansion



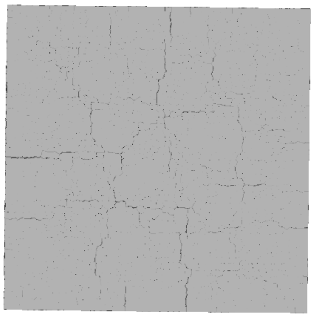
(E) Case 4: 0.8577% Expansion

FIGURE 1.50: 3D Surface Cracks Expansion Intensified 75x75x75mm (Deformation x 10)

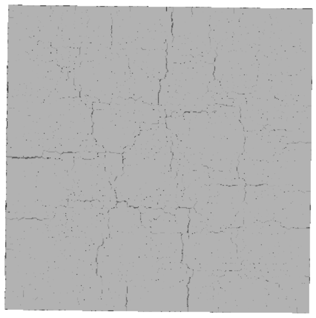
1.5.4.2 Expansion Intensified 100x100X100mm at Center of Model

Initial Strain (Each Step)	Expanding Steps	Final Expansion[%]
0	0	0
0.001	20	0.2
0.002	20	0.4087
0.004	20	0.6191
0.006	20	1.0454

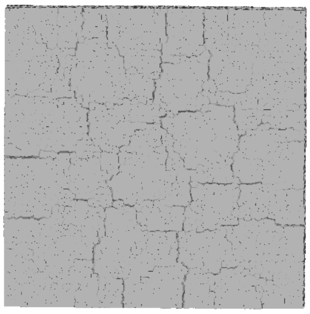
TABLE 1.14: One Dimensional Expansion Ratio in Expansion Intensified 100x100X100mm at Center of Model DEF Model Simulation



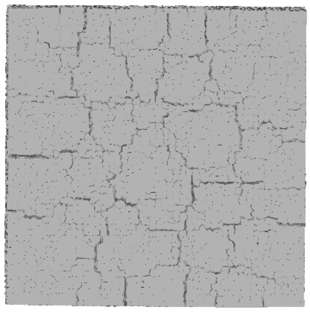
(A) Case 0: 0% Expansion



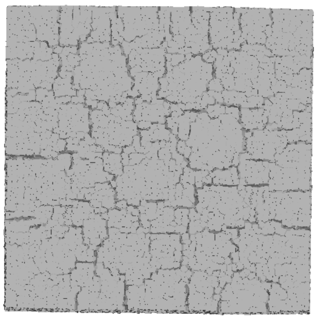
(B) Case 1: 0.1671% Expansion



(C) Case 2: 0.3380% Expansion



(D) Case 3: 0.5118% Expansion



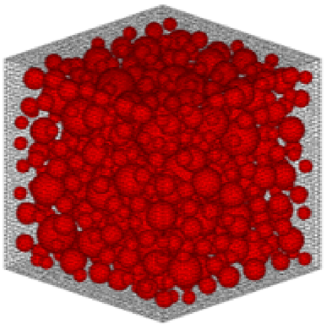
(E) Case 4: 0.8577% Expansion

FIGURE 1.51: 3D Surface Cracks (Single Side View) Expansion Intensified 75x75x75mm (Deformation x 10)

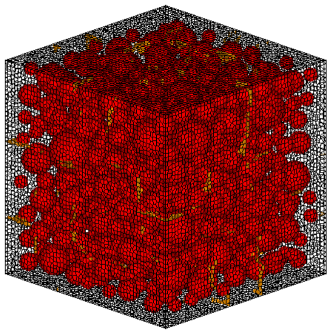
From Figure ??, Figure 1.51, Figure ?? and Figure 1.55, it can be seen that when intensified the DEF expansion at the center 75x75x75mm, still the characteristic map cracking pattern can be achieved, which is similar to 50x50x50mm case.

However, when comparing to uniformed overall expansion (DEF expansion at the center 75x75x75mm), the increasing of the concrete volume is achieved without generating significant surface cracks. This simulation result is correlated with the research result done by L.Eddy et.al., 2016, concluded as the simply uniformed paste expansion does not present DEF simulation well as it behaves in reality.

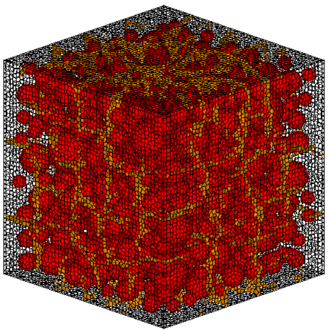
When examined closely of the intersection, it can be seen that no inner crack is happening in the paste for the uniformed expanding case, separation only happens between the



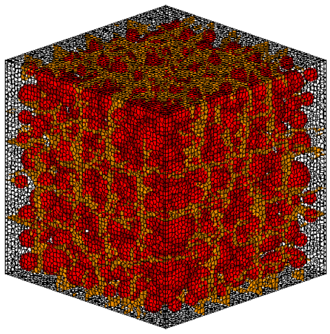
(A) Case 0: 0% Expansion



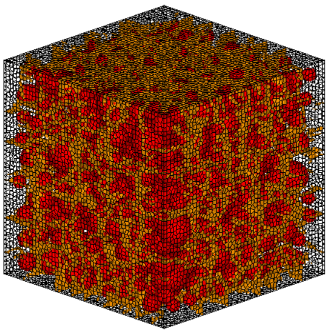
(B) Case 1: 0.1671% Expansion



(C) Case 2: 0.3380% Expansion



(D) Case 3: 0.5118% Expansion



(E) Case 4: 0.8577% Expansion

FIGURE 1.52: 3D Inner Cracks Expansion Intensified 75x75x75mm

surface of aggregate and paste, which is different with other 2 cases.

With expansion intensified in the inner part of concrete model, the compressive force concentrated in the inner part of the model, while outer parts are under tension. This unbalanced force generates cracks at the surrounding part of the concrete, preset as map cracking pattern at the surface view. This cracking pattern is also correlated with the observation form A.Awasthi in his investigation of DEF deteriorated Indian concrete sleeper in 2016.

Figure here.

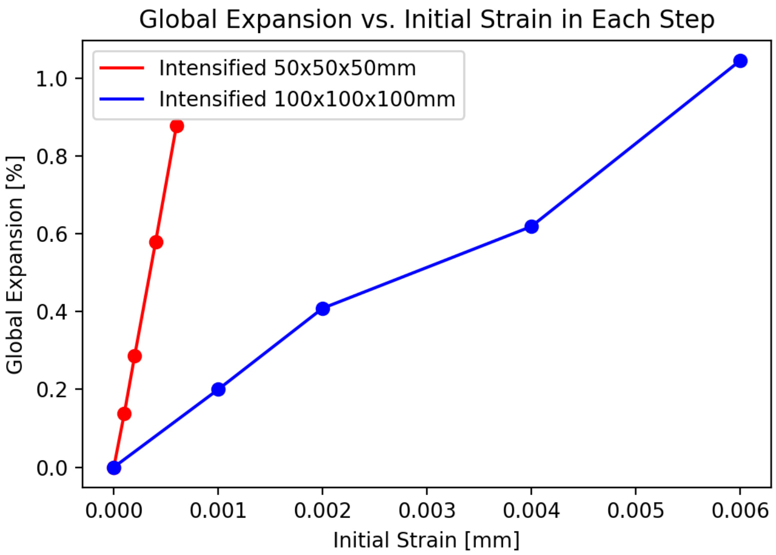
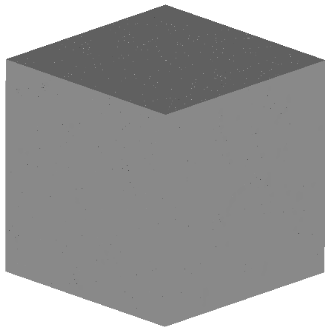
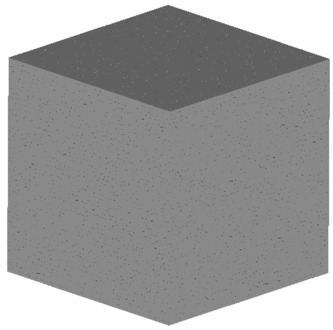


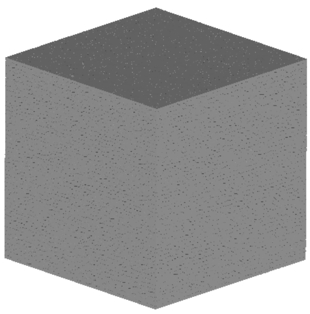
Figure 1.53: Global Expansion vs. Step



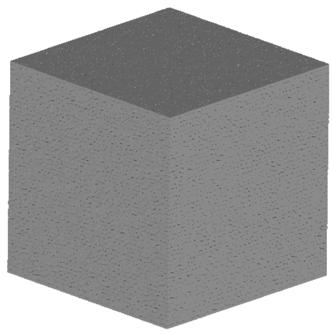
(A) Case 0: 0% Expansion



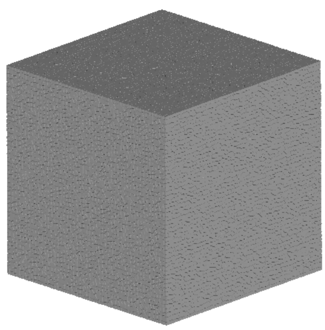
(B) Case 1: 0.2% Expansion



(C) Case 2: 0.4087% Expansion

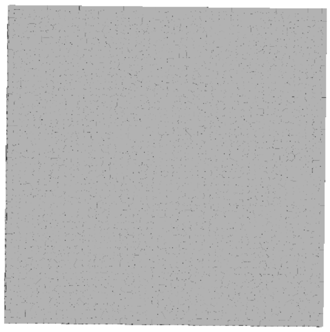


(D) Case 3: 0.6191% Expansion

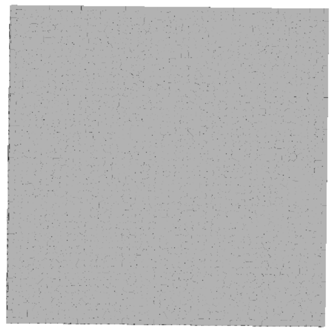


(E) Case 4: 1.0454% Expansion

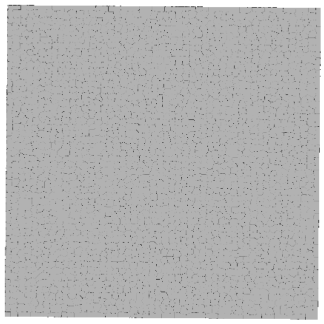
FIGURE 1.54: 3D Surface Cracks Expansion Intensified 100x100X100mm (Deformation x 10)



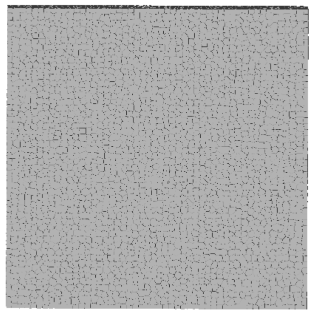
(A) Case 0: 0% Expansion



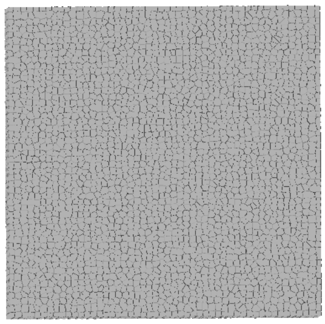
(B) Case 1: 0.2% Expansion



(C) Case 2: 0.4087% Expansion

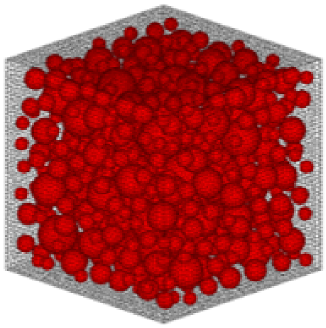


(D) Case 3: 0.6191% Expansion

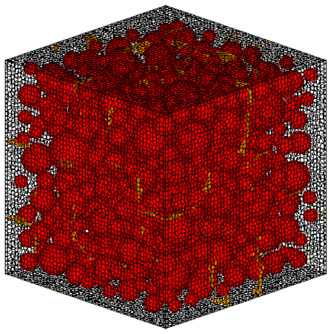


(E) Case 4: 1.0454% Expansion

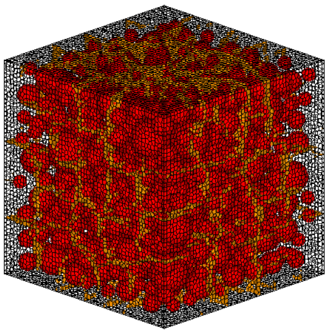
FIGURE 1.55: 3D Surface Cracks (Single Side View) Expansion Intensified 100x100X100mm (Deformation x 10)



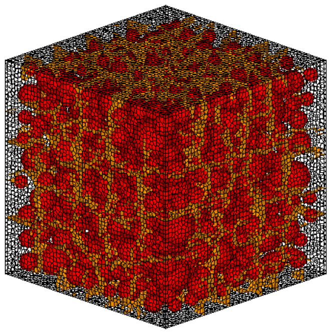
(A) Case 0: 0% Expansion



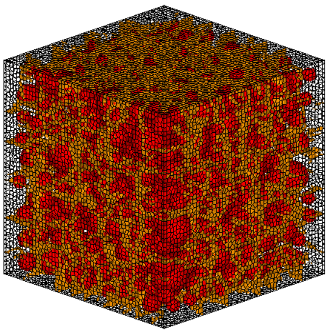
(B) Case 1: 0.2% Expansion



(C) Case 2: 0.4087% Expansion

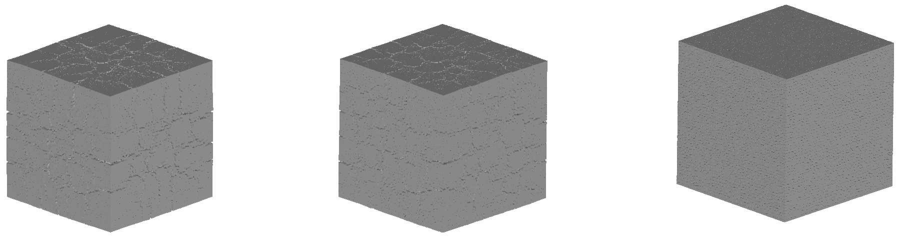


(D) Case 3: 0.6191% Expansion



(E) Case 4: 1.0454% Expansion

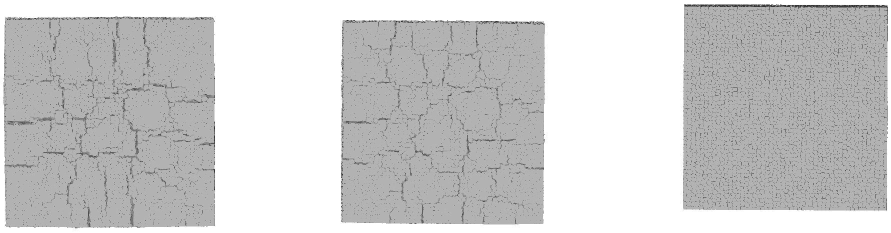
FIGURE 1.56: 3D Inner Cracks Expansion Intensified 100x100X100mm (Deformation x 10)



(A) Intensified 50x50x50mm 0.5795% Expansion

(B) Intensified 75x75x75mm 0.5118% Expansion

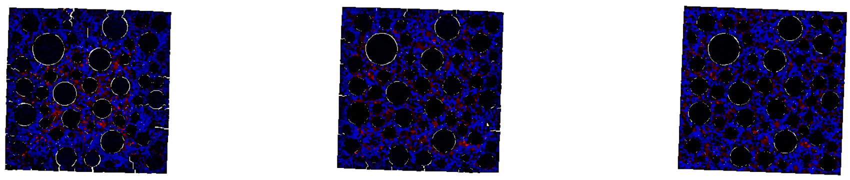
(C) Intensified 100x100x100mm 0.6191% Expansion



(D) Intensified 50x50x50mm 0.5795% Expansion

(E) Intensified 75x75x75mm 0.5118% Expansion

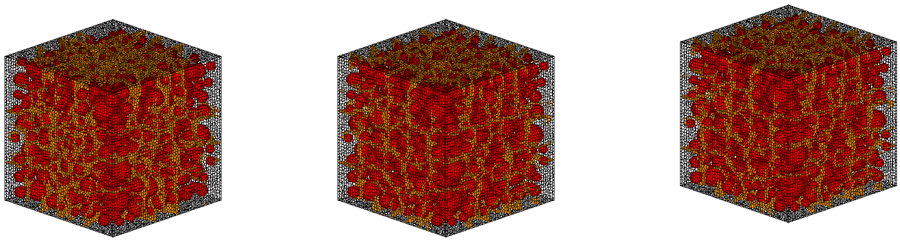
(F) Intensified 100x100x100mm 0.6191% Expansion



(G) Intensified 50x50x50mm 0.5795% Expansion

(H) Intensified 75x75x75mm 0.5118% Expansion

(I) Intensified 100x100x100mm 0.6191% Expansion



(J) Intensified 50x50x50mm 0.5795% Expansion

(K) Intensified 75x75x75mm 0.5118% Expansion

(L) Intensified 100x100x100mm 0.6191% Expansion

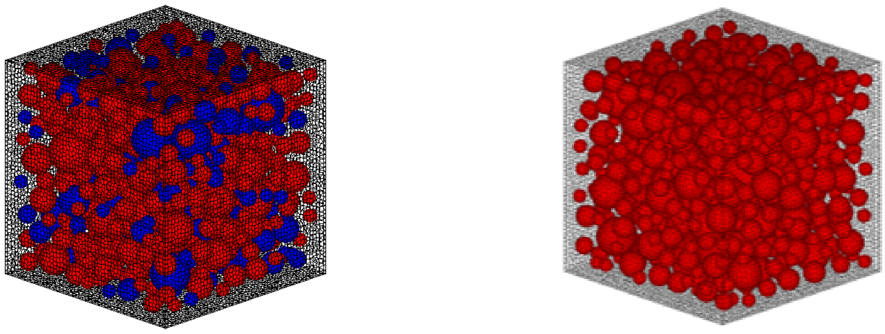
FIGURE 1.57: Comparing between different DEF Expansion Intensified Cases

1.6 Comparing Between ASR Expansion and DEF Expansion Simulation Result

Here the 2 expansion simulation results are compared to analysis the similarities and difference between ASR and DEF expansion.

For ASR, 100x100x100mm model with 30% aggregate is chosen, of which 75% of total aggregates are ASR reactive.

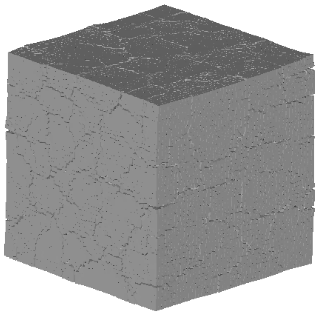
For DEF, same 100x100x100mm model with 30% aggregate is using, of which the 75x75x75mm at the center part is given intensified DEF expansion, and decreased gradually in the surrounding part.



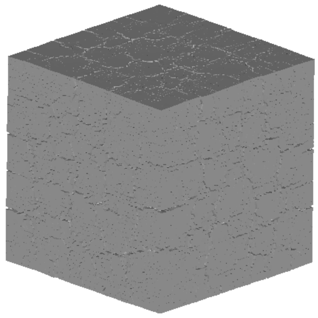
(A) Model for ASR Expansion

(B) 30% Coarse Aggregate

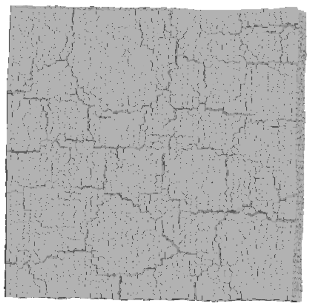
FIGURE 1.58: Model for DEF Expansion



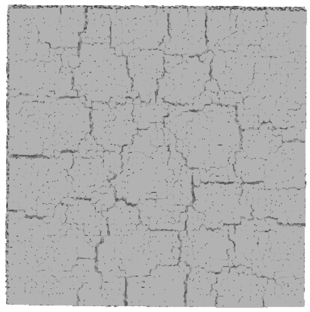
(A) 75% ASR Reactive Aggregate,
3D Surface Cracks, 0.4223% Expansion



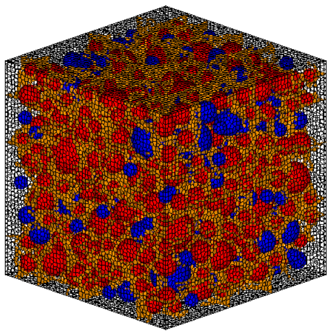
(B) 75x75x75mm Intensified,
3D Surface Cracks, 0.5118% Expansion



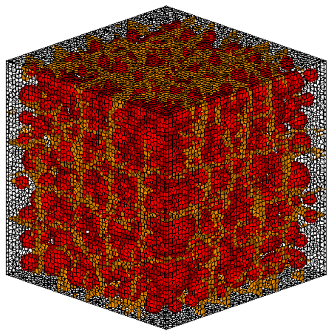
(C) 75% ASR Reactive Aggregate,
Surface Sideview, 0.4223% Expansion



(D) 75x75x75mm Intensified DEF,
Surface Sideview, 0.5118% Expansion



(E) 75% ASR Reactive Aggregate,
Inner Crack, 0.4223% Expansion



(F) 75x75x75mm Intensified DEF,
Inner Crack, 0.5118% Expansion

FIGURE 1.59: Cracks Compare Between ASR Expansion and DEF Expansion Simulation Result

From Figure it can be seen that at a relatively close global expansion ratio, the surface cracking pattern of ASR expansion and DEF expansion can be very close.

However, the inner crack distribute is not exactly the same in these 2 cases. Clear cross alike distribution can be seen in DEF expanded case but not in ASR case.

This can also be confirmed by the cross-section view (Figure 1.60), where in middle of each face of DEF expanded model concentration of crack perpendicular to surface is shown. Besides, for the DEF expansion, the inner part of the model is more integrated comparing to ASR case, with almost no crack inside.

This may indicate with similar outside cracking damage level, deteration caused by DEF expansion is less severe compared with ASR expansion.

(A) 75% ASR Reactive Aggregate, Cross Section, 0.4223% Expansion

(B) 75x75x75mm Intensified DEF, Cross Section, 0.5118% Expansion

FIGURE 1.60: Cross Section Compare Between ASR Expansion and DEF Expansion Simulation Result (Deformation x 10)

Crack Width [mm]	ASR A30P75 0.4223% Expansion Total Cracked Interfaces	DEF A30I75 0.5118% Expansion Total Cracked Interfaces
0.00000 - 0.00005	316744	373019
0.00005 - 0.00010	286704	335814
0.00010 - 0.00020	263943	299690
0.00020 - 0.00050	234672	249242
0.00050 - 0.00100	183238	177030
0.00100 - 0.00300	131553	113350
0.00300 - 0.01000	42432	42207
0.01000 - 0.03000	275	240
0.03000 - 0.10000	0	0
0.1000+	0	0

TABLE 1.15: Expansion in Each Step for A30 P75 Case 3

PLOT

When comparing the cracked interfaced grouped by the width of crack (Tabel 1.15), it also can be seen that comparing to ASR expansion, cracks in DEF expansion simulation result is more concentrated in smaller crack width, which is under 0.001mm in this comparison.

ASR and DEF expansion, though similar on their surface cracking, are different in their mechanism and inner condition. And the simulation used in this research can properly reproduce not only the similarities but also the difference between them.

1.7 Conclusion

1. By checking the 10x10x10mm single aggregate model, the feasibility of simulate ASR and DEF expansion in confirmed, by checking the cracking generation and inner stress generation. In small scale around aggregate, by introducing initial strain into interfaces, concrete would expanse as the method assumed.

2. By using the proposed constitutive models, the simulation results of expansion behavior in ASR can be represented. Characteristic map cracking pattern is shown in all cases under different condition, and generate as larger expansion introduced.

3. When keeping all other factors the same, as the total coarse aggregate percentage decrease, the map cracking pattern still present, but is more sparse.

4. When keeping all other factors the same, as the total percentage of reactive coarse aggregate decrease, the map cracking pattern also becomes more sparse.

5. The proposed constitutive models, with non-uniform expansion, can represent the characteristic map cracking pattern of DEF.

6. When only change the ratio of coarse aggregate contained, the behavior does not change much, only when comparing cracked interfaces number numerically it can be noticed that lower coarse aggregate case having more smaller cracks rather can larger cracks compare to higher aggregate cases.

7. When changing the range of intensified expansion zone for DEF, the cracking patterAn also shows some difference, but generally very close in all cases with intensification.

8. Though both ASR and DEF shows characteristic map crack pattern in the surface, the inner cracking condition is very different. More large cracks are happening in the center of ASR damaged cases, while the inner part of the DEF expanded model generally remains unchanged under naked eyes.

1.8 References