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Transient Response of RC Panel Protected with Slurry Infiltrated Micro Reinforced Concrete Jacket Under Blast Loading

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Abstract: ***With increase in terrorist attacks, there are definite priority to protect the important infrastructure facilities against possible terrorist attacks. In order to improve blast resistance capacity of RCC panel, in present study, it was strengthened with Slurry Infiltrated Micro Reinforced Concrete (SIMRC) jacket. . The SIMRC jacket strengthened RC panel was analyzed under blast load scenario using finite element method based application, ABAQUS. The dynamic behavior of concrete and grout of SIMRC was modeled using concrete damaged plasticity model. The structural response of RC panel without any strengthening was compared with SIMRC strengthened RC panel to investigate effectiveness of SIMRC jacketing to resist blast load. Parametric study was carried out considering SIMRC jacket on single side or both side of RC panel, with different ratio of thickness of jacket to thickness of RC panel (t/D) and different percentage of wire mesh reinforcement for jacket. Simulation of various analysis results were presented in form of displacement time history, distribution of tensile/compressive damage variable explaining the pattern of failure in the RC panel, comparison of distribution of tensile damage variable on front and back jacket, compression damage variable of RC panel. It was observed that for panels with strengthening displacement and damaged areas are reduced as compared to conventional RC panel. The increase in thickness ratio (t/D), percentage of wire mesh reinforcement in jacket also contribute to increase blast resistance capacity of SIMRC Jacket. It was also observed that the jacketing on both side of RC panel is more effective in reducing the displacement and the damage is observed to be spread over the support areas. Obtained results through present study demonstrate the effective use of SIMRC jacketing as blast mitigation measure.***

Index Terms: ***blast load, concrete damaged plasticity model, numerical simulation, Slurry Infiltrated Micro Reinforced Concrete***

I. INTRODUCTION

Infrastructure facilities like public buildings, hospitals, schools are designed for conventional load combination without considering special load like blast load. The key elements of any critical infrastructure facilities like columns, external wall should be strengthen to resist such special loads. Steel jacketing [1], Aramid Fiber Reinforced Plastic (AFRP) [2] Hybrid Carbon Fiber Reinforced Polymer –Polyurea (CFRP-UP) [3], Carbon Fiber Reinforced Polymer (CFRP) [4], Fiber Reinforced Polymer wrapping (FRP) [5] etc. are strengthening alternatives to increase blast resistance capacity of the structure. The present study focus on Slurry Infiltrated Micro Reinforced concrete (SIMRC) as strengthening option to resist the blast load. Slurry Infiltrated Micro Reinforced Concrete (SIMRC) commercial known as DUCON, has high energy absorption of large deformations due to higher strength and ductility. These key characteristics of DUCON increases its applicability for blast and ballistic protection without fragmentation at reduced thickness as compared to ordinary reinforced concrete [6]. Alostaz et al. 2012 [7] performed threat, vulnerability and risk assessment (TVRA) for exterior wall using steel plates, FRP and Slurry Infiltrated Micro Reinforced concrete (SIMRC) and indicated that the SIMRC hardening was successfully work for reduction in breach and airborne debris inside the room. The experimental study using shock tube and single degree of freedom analysis were conducted by Stolz et al. (2014) [8] to investigate the bearing resistance of ductile concrete (DUCON) plate under blast load condition. It was demonstrated using damage curves that the DUCON panel exhibit highest bearing capacity under blast loading condition as compare to normal strength concrete and ultra-high performance concrete. In present study transient response of reinforced concrete (RC) panel strengthened with SIMRC jacket were studied by finite element method using computer application ABAQUS. The concrete for RC panel and grout for SIMRC jacket were modeled using concrete damaged plasticity model available in ABAQUS. The reinforcement in RC panel and wire mesh in SIMRC jacket were modeled using plastic kinematic model. The parametric study was carried out to evaluate the effect of different ratio of thickness of SIMRC jacket to thickness of RC panel (t/D) and different percentage of wire mesh reinforcement for SIMRC jacket on single side or on both side of RC panel under blast load condition. The results of study were obtained in form of displacement time history, distribution of compressive damage variable and distribution of tensile damage variable.

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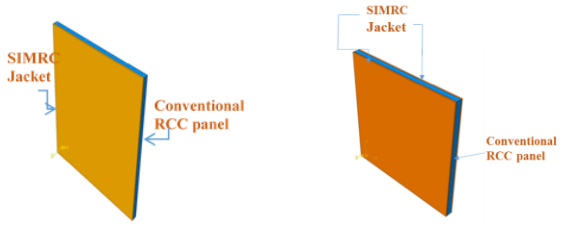
II. NUMERICAL MODELING OF SIMRC STRENGTHEN RC PANEL

Model Geometry

Typical reinforced concrete panel 1250mm x 1250 mm x 50 mm size with SIMRC jacket in the direction of blast load and both side of RC panel is presented in Fig. 1(a) and 1(b) respectively. Panel with SIMRC Jacket was considered to be simply supported from two opposite sides. The RC panel is reinforced with 6 mm diameter reinforcement while SIMRC jacket have 1 mm diameter wire mesh as reinforcement. The typical reinforced concrete panel with SIMRC Jacket was subjected to blast load of 0.52 kg of TNT at 500 mm standoff distance from center of the RC panel. Various cases used for parametric study are presented in Table I.



(a) (b)

Figure 1 Typical reinforced concrete panel with (a) SIMRC Jacket on one side (b) SIMRC Jacket on both side

Table I Various Cases for Parametric Study

Case No	Position of Jacket	Jacket to panel thickness ratio (t/D)	Percentage of steel
Case 1	One side of panel	0.2	3
Case 2	One side of panel		4
Case 3	One side of panel		6
Case 4	Both side of Panel		3
Case 5	Both side of Panel		4
Case 6	Both side of Panel		6
Case 7	One side of panel	0.3	3
Case 8	One side of panel		4
Case 9	One side of panel		6
Case 10	Both side of Panel		3
Case 11	Both side of Panel		4
Case 12	Both side of Panel		6
Case 13	One side of panel	0.5	3
Case 14	One side of panel		4
Case 15	One side of panel		6
Case 16	Both side of Panel		3
Case 17	Both side of Panel		4
Case 18	Both side of Panel		6

Modeling of Blast load

Detonation of explosive material generates the strong shock wave as a result of propagation of pressure front into surrounding atmosphere. The blast wave is characterized by an almost instantaneous rise from ambient pressure to peak incident pressure P_{so} (Fig. 2). P_{so} the incident pressure decays to the ambient value in positive phase duration (t_o). This is followed by negative phase usually much longer than the positive phase and having maximum negative pressure $P_{s\bar{o}}$ as well as a reversal of particle flow. The positive phase has is more important in a design as compared to negative pressure. In the present study the air blast loading data was provided by CONWEP model in conjunction with incident wave loading definition.

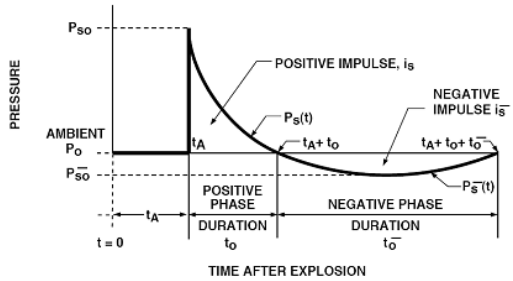


Figure 2 Typical Pressure-Time History of an Air blast in Free Air [9]

Material modelling for concrete and grout for SIMRC

In ABAQUS, material models that can be used to simulate the concrete material properties are smeared cracking model, brittle cracking model and concrete damaged plasticity model. In the present study, concrete damaged plasticity model is used to model conventional reinforced concrete and SIMRC grout. The yield criterion, flow rule and hardening rule are essential elements of the model based on plasticity theory [10]. The plastic damage concrete model in ABAQUS uses yield condition based on the yield function proposed by [10] as shown in Equation 1. The abbreviation and coefficients of Equation 1 can be referred from [10].

$$F = \frac{1}{1-\alpha}\left(\alpha I_1 + \sqrt{3J_2} + \beta[\sigma_{max}] - \gamma[-\sigma_{max}]\right) \quad (1)$$

With

$$\alpha = \frac{\left(\sigma_{b0}/\sigma_{c0}\right)-1}{2\left(\sigma_{b0}/\sigma_{c0}\right)-1}\ ; 0 \le \alpha \le 0.5,$$

$$\beta = \frac{\sigma_{c0}}{\sigma_{t0}}(1-\alpha) - (1+\alpha),$$

$$\gamma = \frac{3(1-\rho)}{2\rho-1}$$

Where α, β and γ are dimension less constants, ρ is constant whose value ranges from 0.64 and 0.66 to about 0.8

σ_{b0} and σ_{c0} are initial equibiaxial and uniaxial compressive yield stresses, σ_{t0} is initial uniaxial tensile yield stress

In the model proposed by [10], the total damage is assumed to correspond to the vanishing of the cohesion as in Equation 2

$$F(\sigma) = c \quad (2)$$

The above equation gives good results for monotonic loading but not appropriate for the cyclic behaviour of concrete so [11] proposed the modification in calculation of β which considers two cohesion variables as

$$\beta = \frac{c_c(k)}{c_t(k)}(1-\alpha) - (1+\alpha)$$

Where c_t and c_c are tensile and compressive cohesion respectively.

The modifications proposed by [11] are also incorporated in concrete damaged plasticity model with ABAQUS.
The model considers flow potential G, the Drucker-Prager hyperbolic function as per (Equation 3)

$$G = \sqrt{(\epsilon\sigma_{t0}\tan\psi)^2 + q^2} - p\tan\psi \qquad (3)$$

In (Equation 3) σ_{t0} = the uniaxial tensile stress at failure,
ϵ = the eccentricity of plastic potential surface
ψ = the dilatancy angle measured in p-q deviatory plan at high confining pressure.
Table II and Table III describe concrete damaged plasticity model parameters and properties of concrete and grout of SIMRC used in present study.

Table Concrete Damage Plasticity Model Parameters

K_c	Ψ (˚)	f_{b0}/f_{c0}	ϵ
0.7	31	1.16	0.1

Material modelling of reinforcement and wire mesh

The reinforcement of RC panel and wire mesh for SIMRC jacket are modelled using Kinematic hardening model available with ABAQUS. The material properties for reinforcement bar and wire mesh are indicated in Table IV. The present study consider linear kinematic model which has constant hardening modulus. The evolution law of this model (as indicated in Equation 4) consist of linear kinematic hardening component that describes the translation of the yield surface in stress space through the backstress α [12].

$$\dot{\alpha} = C\left(\frac{1}{\sigma^0}\right)(\sigma - \alpha)\dot{\varepsilon}^{pl} \qquad (4)$$

Where $\dot{\varepsilon}^{pl}$ the equivalent plastic strain rate and C is is the kinematic hardening modulus. In this model the equivalent stress defining the size of the yield surface, σ^0 remains constant. Two yield stresses $\sigma|_0$ and σ are required to define behaviour are yield stress at zero plastic strain and yield stress at a finite plastic stain $\dot{\varepsilon}^{pl}$ respectively.

The linear kinematic hardening modulus C can be determined from following Equation 5.

$$C = \frac{\sigma - \sigma|0}{\varepsilon^{pl}} \qquad (5)$$

III. RESULTS AND OBSERVATIONS

The centre node of the RC panel strengthen with SIMRC panel was selected to monitor displacement time history for the RC panel with SIMRC jacket. The results of various parametric studies considering the effect of thickness of jacket to thickness of RC panel i.e. (t/D) ratio 0.2, 0.3 and 0.5 with different percentage of wire mesh reinforcement i.e. 3%, 4% and 6% are presented in following section.

Table I Material Properties of Concrete and Grout For Simrc

Conventional Reinforced Concrete	**Value**
Young's Modulus E (MPa)	28300
Compressive Yield Stress (MPa)	40
Tensile Yield Stress (MPa)	4.2
Grout for SIMRC	**Value**
Young's Modulus E (MPa)	37563
Compressive strength (MPa)	45
Tensile strength (MPa)	4.8

Table II Material Properties for Steel Reinforcement and Wire Mesh

Parameter	**Value**
Steel Reinforcement	
Young's Modulus E (MPa)	2×10^5
Yield strength (MPa)	290
Ultimate strength (MPa)	710
Maximum strain	0.3
Wire mesh for SIMRC	
Yield strength (MPa)	303
Ultimate strength (MPa)	414
Ultimate strain	0.18

Displacement time history

Fig. 3 indicates the displacement time history generated due to blast load with 0.52 kg of TNT charge weight on RC panel protected with SIMRC Jacket (t/D ratio 0.2). It can be observed from the Fig. 3 that the maximum displacement 9.35 mm was observed in case of SIMRC strengthen RC panel in the direction of application of blast with 3% wire mesh reinforcement while minimum displacement mm 5.86 was observed in case of observed in case of RC panel protected with SIMRC Jacket on both side of panel with 6% wire mesh reinforcement.

The displacement time histories generated for the 0.52 kg of TNT charge weight on panel protected with SIMRC Jacket (t/D = 0.3) are indicated in the Fig. 4. It can be observed from the Fig. 4 that the maximum displacement 7.27 mm was observed in case of RC panel protected on single side with the SIMRC jacket having 3% wire mesh reinforcement while minimum displacement 4.01 mm was observed in case of RC panel protected with SIMRC jacket on both side of panel with 6% wire mesh reinforcement

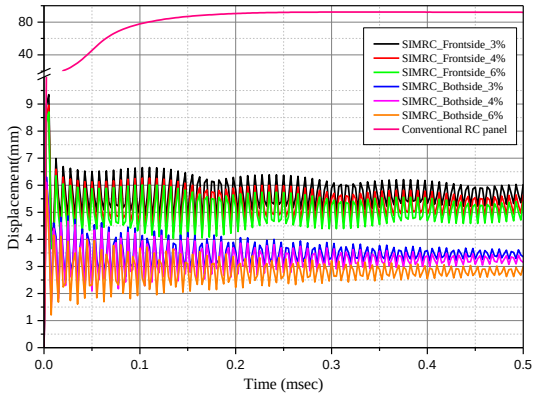


Figure 3 Displacement time history for RC panel protected with SIMRC jacket (t/D = 0.2)

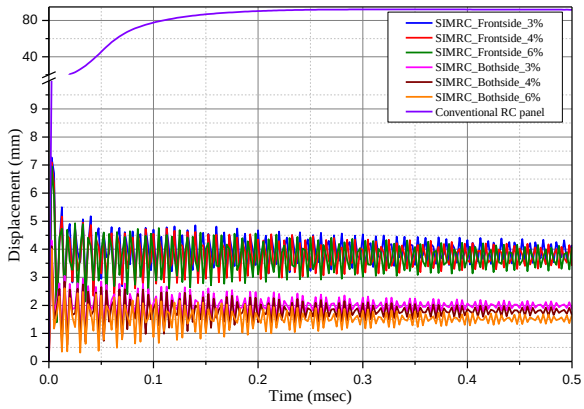


Figure 4 Displacement time history for RC panel protected with SIMRC jacket (t/D = 0.3)

Fig. 5 indicates the displacement time history generated due to blast load with 0.52 kg of TNT charge weight on the protected with SIMRC Jacket having thickness ratio (t/D) = 0.5. It can be observed from the Fig. 5 that the maximum displacement 5.41 mm was observed in case panel with SIMRC jacket having 3% wire mesh reinforcement on single side while minimum displacement 1.52 mm was observed in case of panel with SIMRC jacket having 6% wire mesh reinforcement on both side of RC panel.

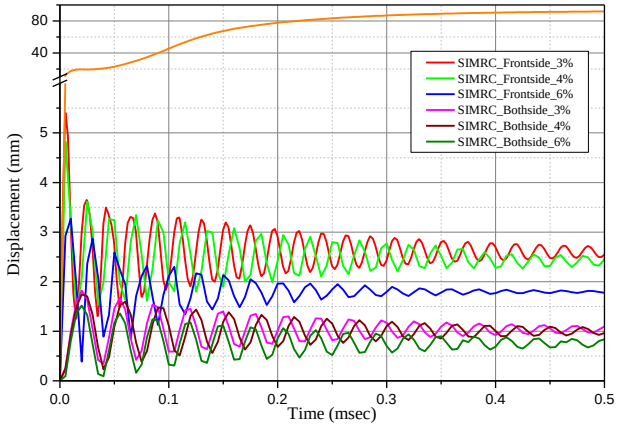


Figure 5 Displacement time history for RC panel with SIMRC (t/D = 0.5)

The comparison of maximum displacement of various case for parametric study is indicated in Fig. 6. It can be observed that the maximum displacement 94.91 mm was observed for the RC panel without any protection. The maximum displacement of RC panel without any protection was reduced up to 9.35 m in case of SIMRC jacket on single side of RC panel with 3% wire mesh reinforcement. The minimum displacement among all SIMRC jacket cases was observed 1.52 mm in case of RC panel with SIMRC jacket on both side of panel with wire mesh reinforcement 6%.

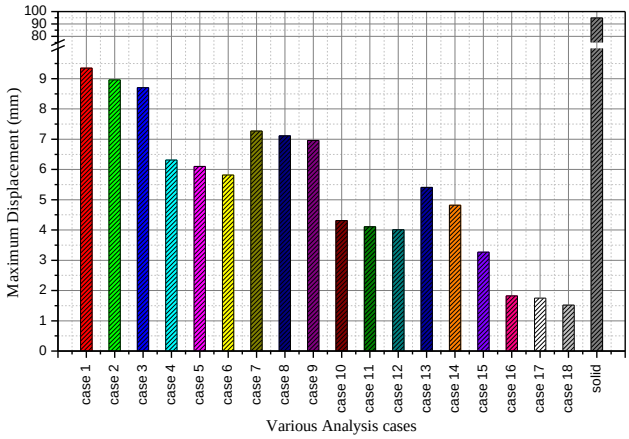


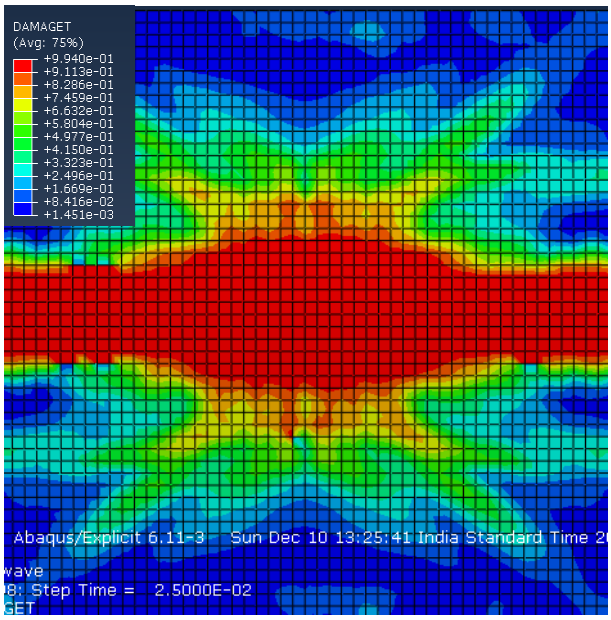
Figure 6 Comparison of maximum displacement of various cases for parametric study

The damage of RC panel was predicted by phenomenon of cracking under tensile damage and crushing under compressive damage. The values of tensile damage variable or compressive damage variable nearer to one indicate the failure of RC panel by cracking or by crushing respectively.

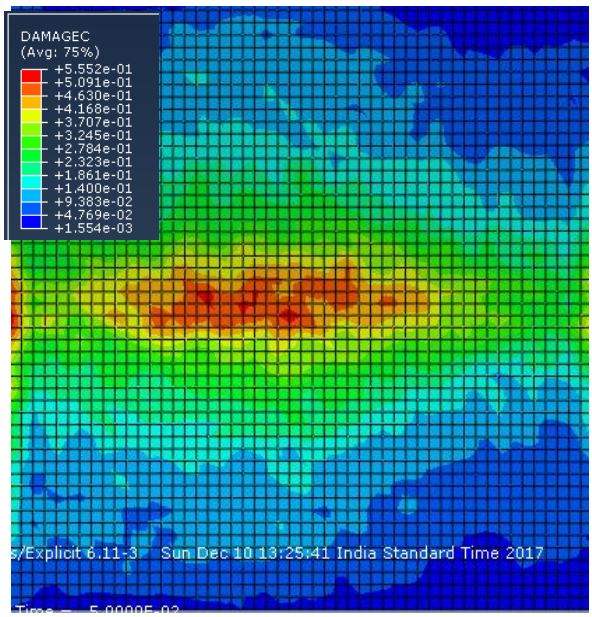
Damage prediction

The distribution of tensile damage variable on back side of RC panel is indicated in Fig. 7. The red cells indicate maximum value of tensile damage variable.

It can be observed from distribution of tensile damage variable for conventional RC panel that the damage is localized along the strip parallel to support, while the compression damage variable does not reach the value 1. Fig. 8 indicates the distribution of tensile damage variable for RC panel with SIMRC jacket with thickness ration 0.2. Fig. 8(a), (b), and (c) indicate the tensile damage variable of panel with SIMRC jacket having 3%, 4% and 6% wire mesh reinforcement on single side i.e. in the direction of application of blast load. It can be observed that the localized damage is concentrated near the strip parallel to support and reducing as increase in percentage of reinforcement. Fig. 8 (d)-(f) indicate the tensile damage variable of RC panel with SIMRC jacket having 3%, 4% and 6% wire mesh reinforcement on both side of panel. It can be observed that the damage is concentrated near support. Fig. 9 indicates the distribution of tensile damage variable for front and back side for the case 4 to case 6. The distribution of compression damage variable is indicated in Fig. 10. It was observed that the value of compression damage variable is less than 1, hence failure of panel was not governed by crushing. Fig. 11 indicates the distribution of tensile damage variable for RC panel with SIMRC jacket with thickness ratio (t/D=0.3). Fig. 11(a), (b), and (c) indicate the tensile damage variable of RC panel with SIMRC jacket having 3%, 4% and 6% wire mesh reinforcement on single side i.e. in the direction of application of blast load. It can be observed that the localized damage is concentrated near the strip parallel to support and reducing on increase in percentage of reinforcement. Fig. 11 (d)-(f) indicate the tensile damage variable of RC panel with SIMRC jacket having 3%, 4% and 6% wire mesh reinforcement on both side of panel. It can be observed that the damage is concentrated near support. Fig. 12 indicates the distribution of tensile damage variable for front and back side of SIMRC jacket for the case 10 to case 12. The distribution of compression damage variable is indicated in Fig. 13. It was observed that the value of compression damage variable is less than 1, so failure of panel was not governed by crushing Fig. 14 indicates the distribution of tensile damage variable for RC panel with SIMRC jacket with thickness ratio (t/D= 0.5). Fig. 14(a), (b), and (c) indicate the tensile damage variable of RC panel with SIMRC jacket having 3%, 4% and 6% wire mesh reinforcement on single side i.e. in the direction of application of blast load. It can be observed that the localized damage is concentrated near the strip parallel to support and reducing on increase in percentage of reinforcement. Fig. 14 (d)-(f) indicate the tensile damage variable of RC panel with SIMRC jacket having 3%, 4% and 6% wire mesh reinforcement on both side of panel. It can be observed that the damage is concentrated near support. Fig. 15 indicates the distribution of tensile damage variable for front and back side of SIMRC jacket for the case 16 to case 18. The distribution of compression damage variable is indicated in Fig. 16. It was observed that the value of compression damage variable is less than 1, hence in this cases also failure of panel was not governed by crushing.

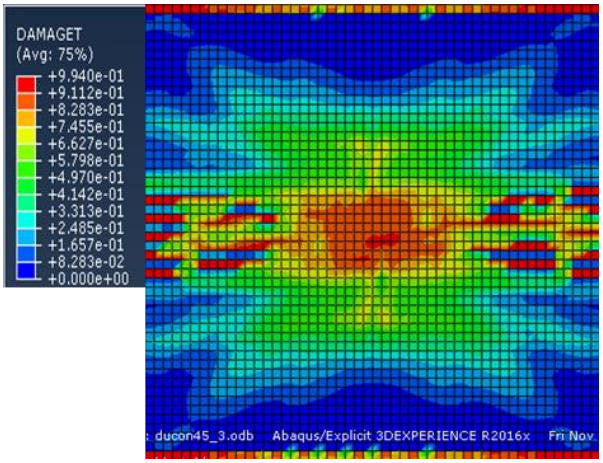


(a)Tension Damage

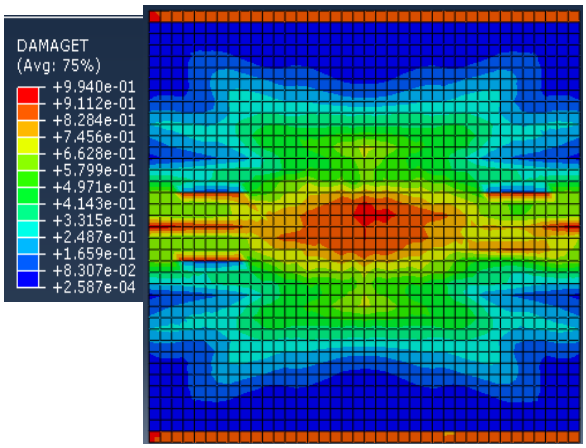


(b) Compression Damage

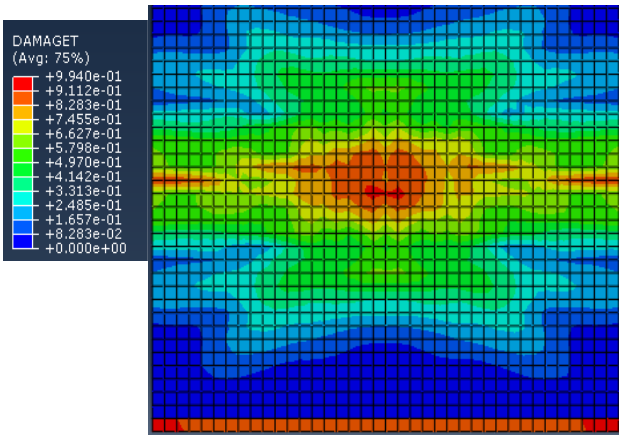
Figure 7 Damage Prediction of Conventional RC panel



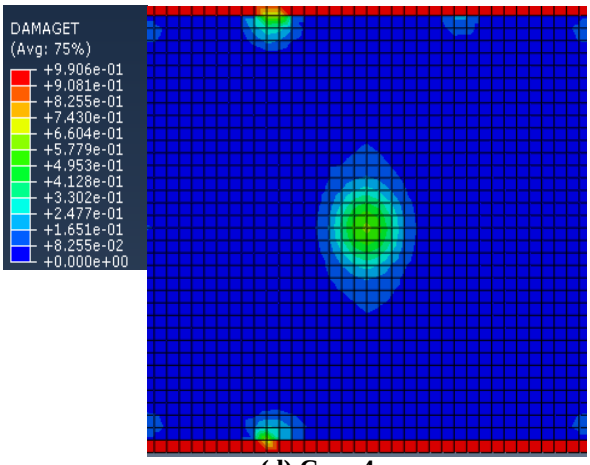
(a) Case 1



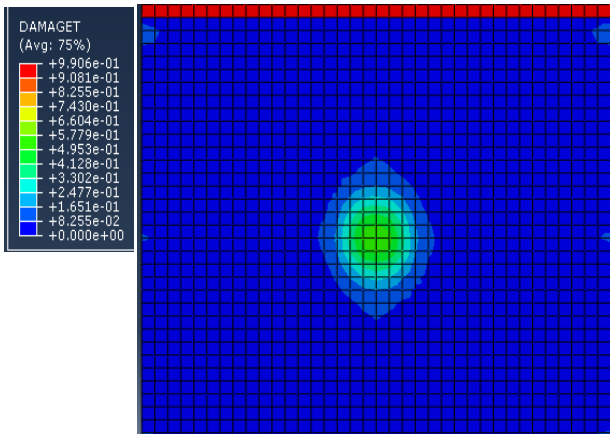
(b) Case2



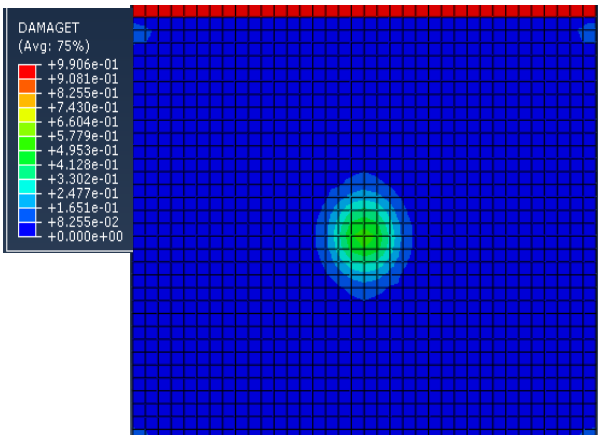
(c)Case 3



(d) Case 4

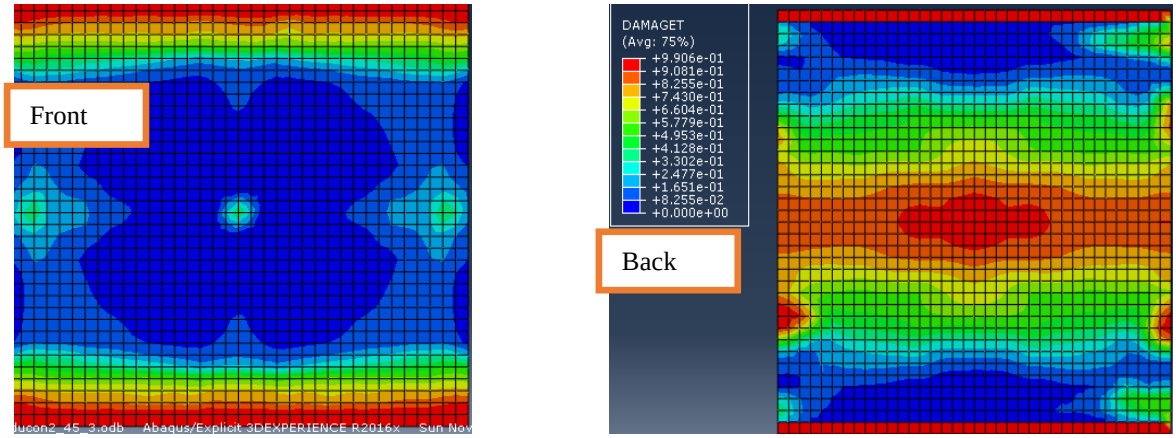


(e) Case 5

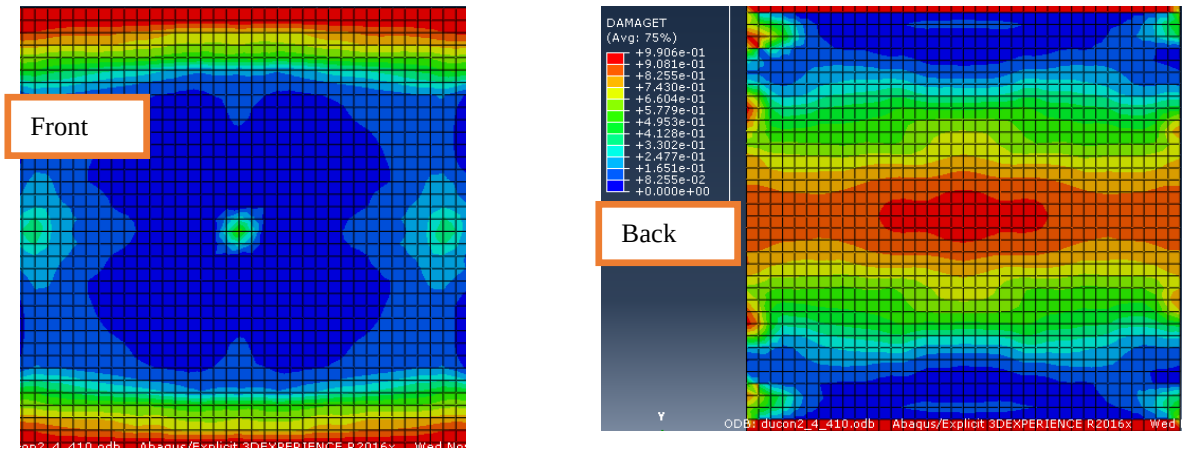


(f) Case 6

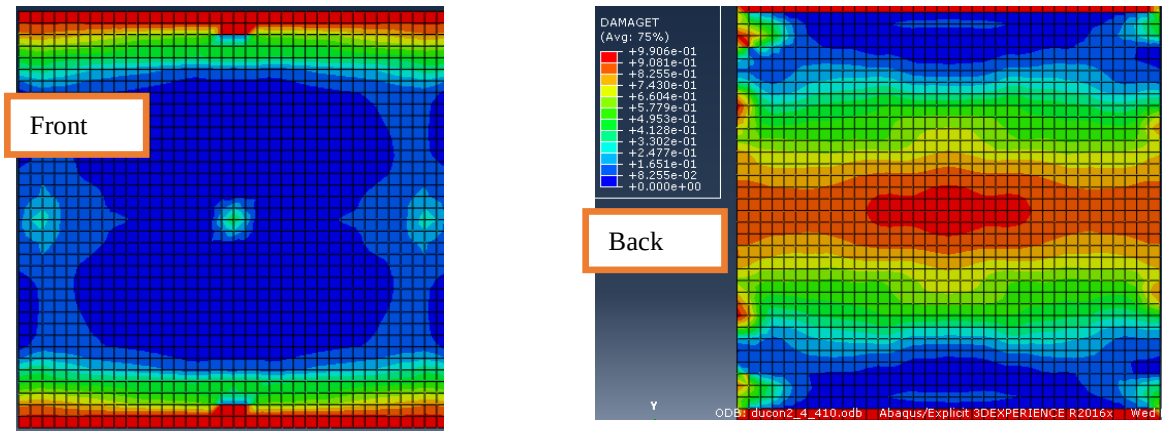
Figure 8 Distribution of Tensile Damage variable for RC panel(t/D =0.2)



Case 4

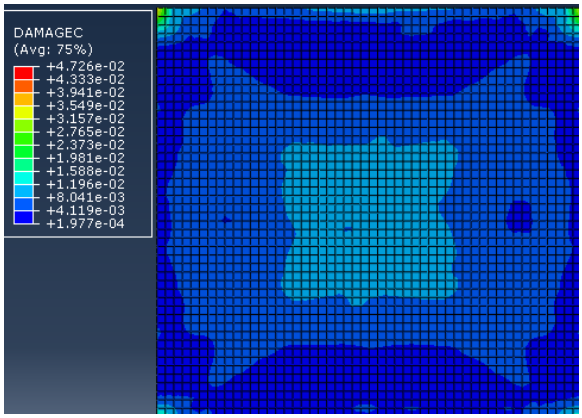


Case 5

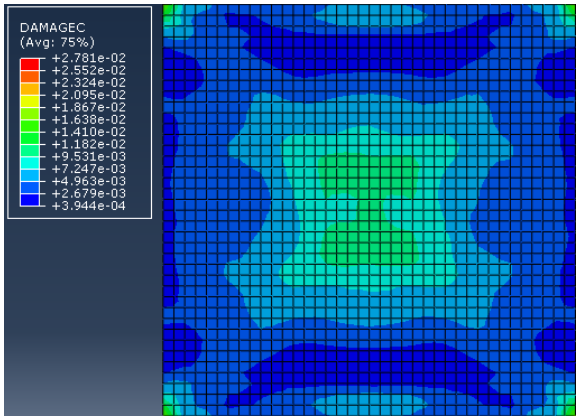


Case 6

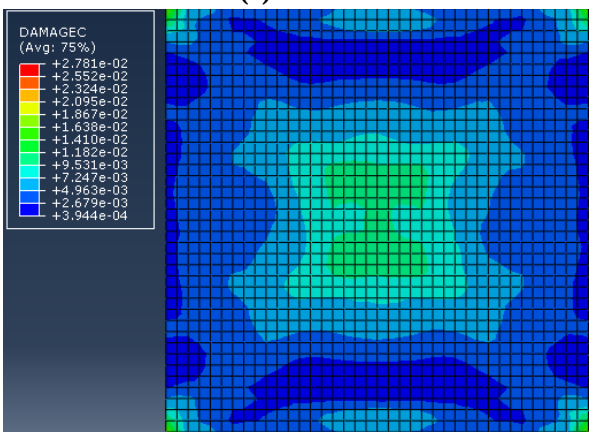
Figure 9 Comparison of Distribution of Tensile Damage variable for front and back jacket (t/D =0.2)



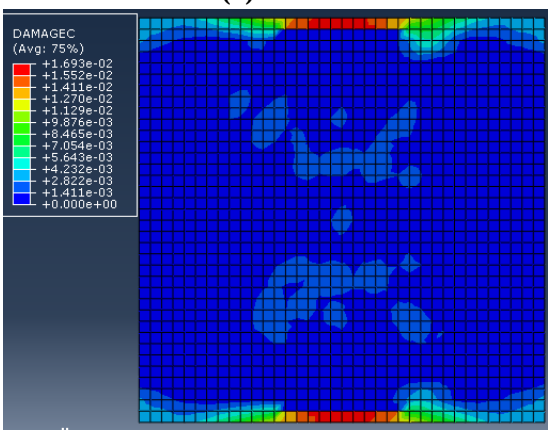
(a) Case 1



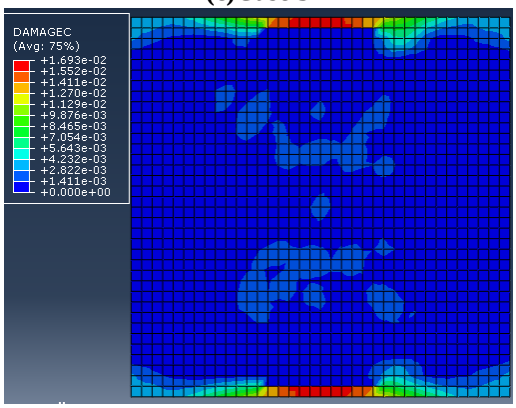
(b) Case2



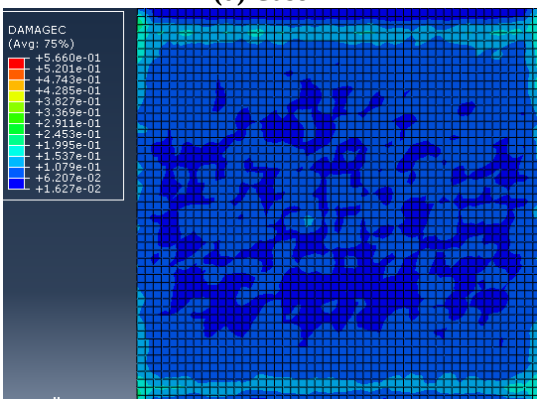
(c)Case 3



(d) Case 4

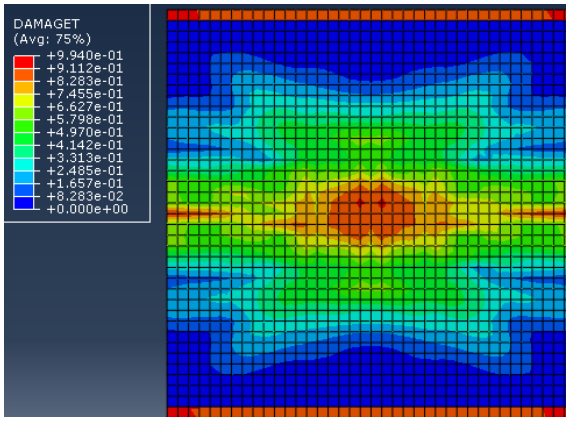


(e) Case 5

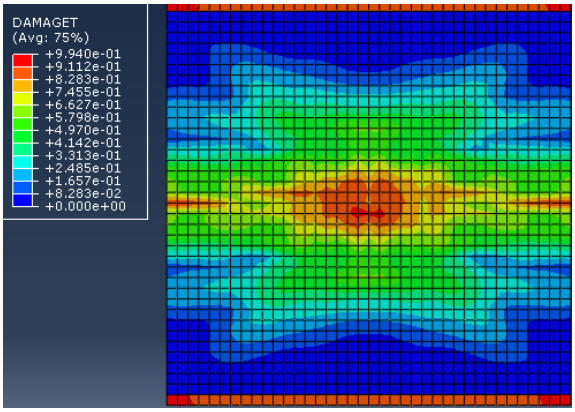


(f) Case 6

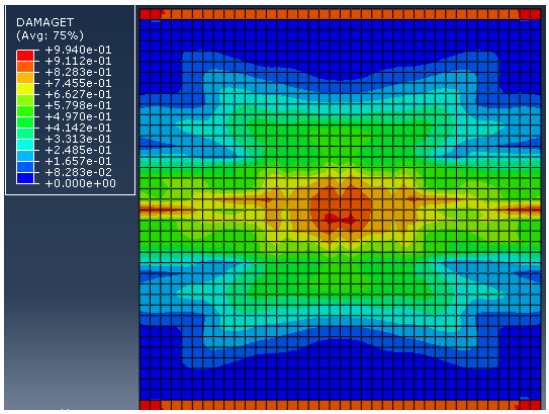
Figure 10 Distribution of compression damage variable for RC panel (t/D =0.2)



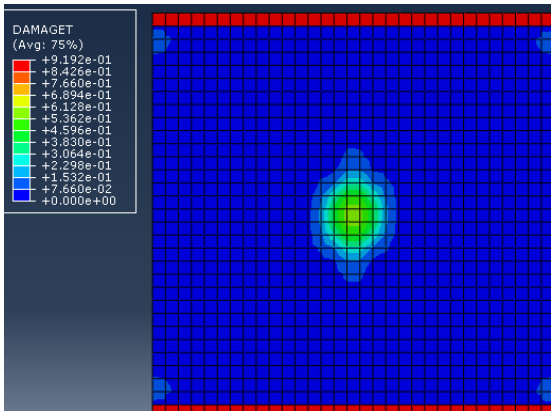
(a) Case 7



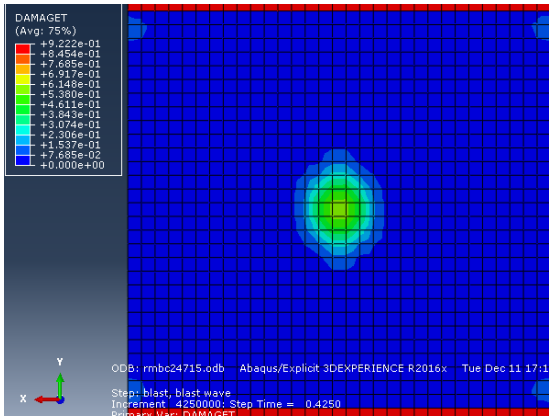
(b) Case8



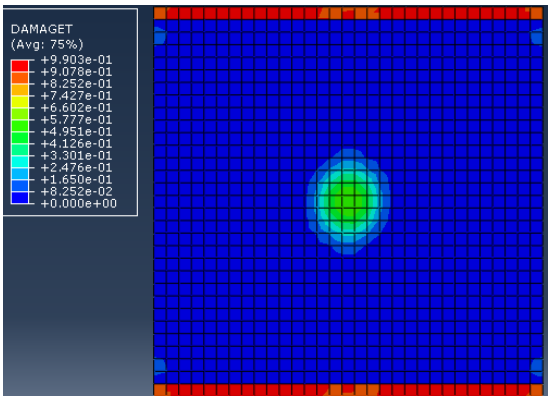
(c)Case 9



(d) Case 10

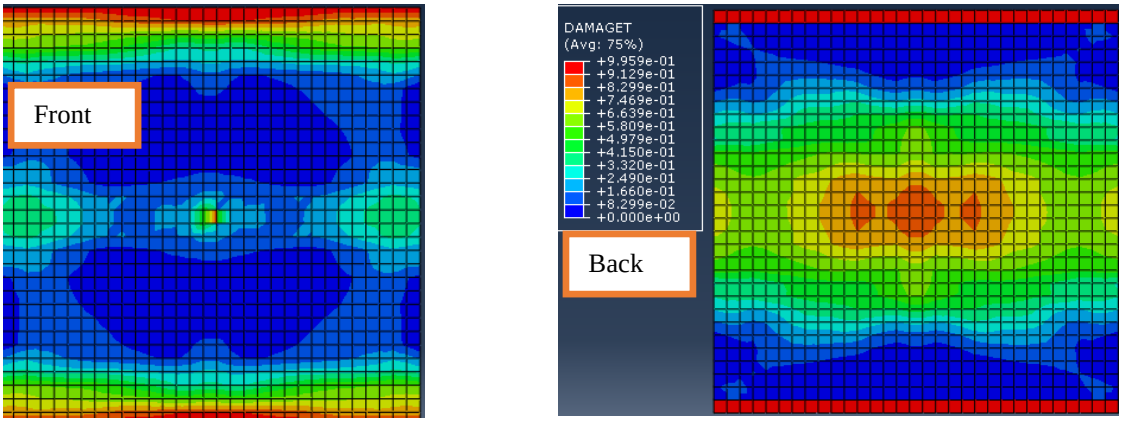


(e) Case 11

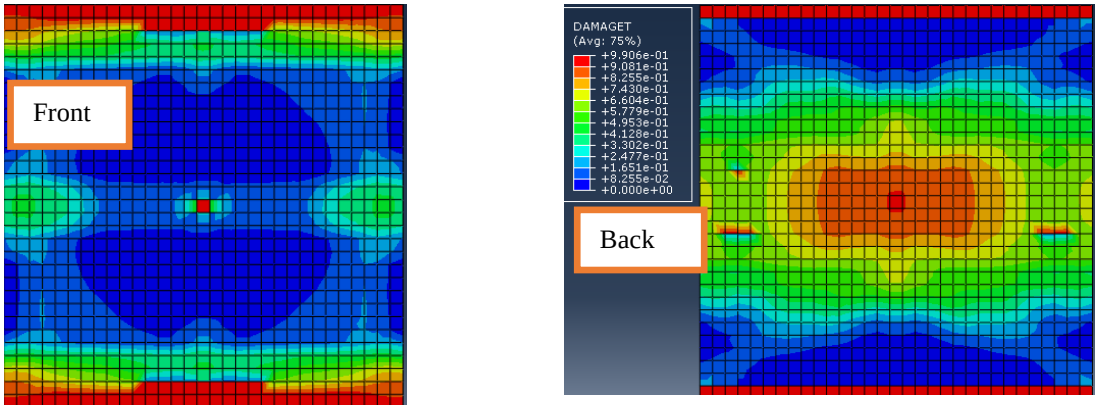


(f) Case 12

Figure 11 Distribution of Tensile Damage variable for RC panel(t/D =0.3)



Case 10



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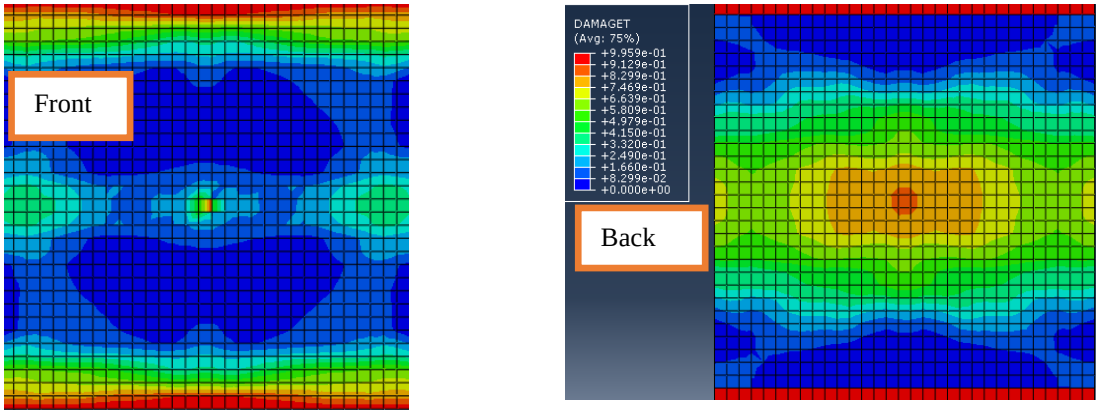
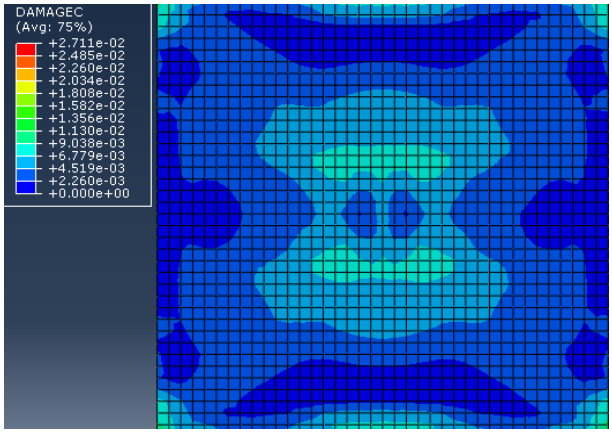


Case 12

Figure 12 Comparison of Distribution of Tensile Damage variable for front and back jacket (t/D =0.3)



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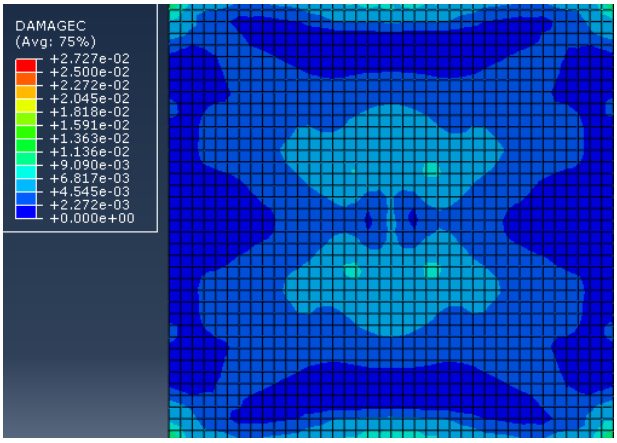
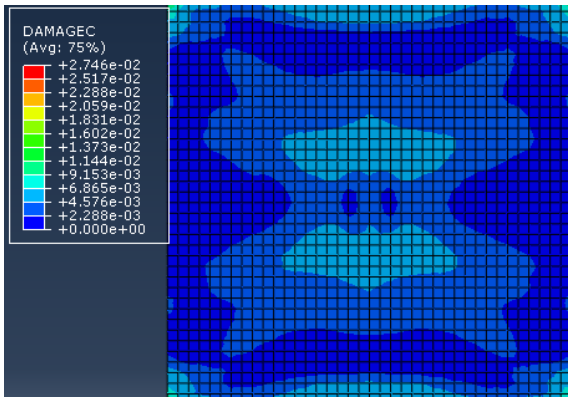
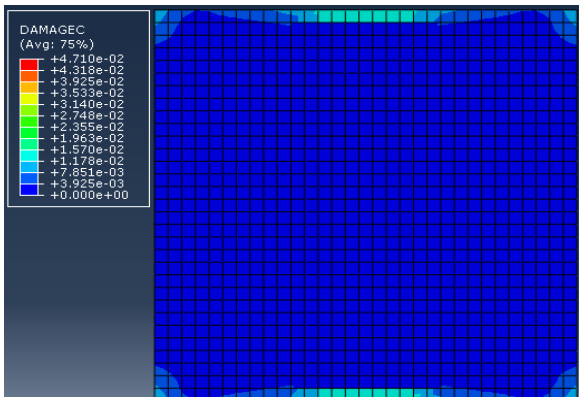


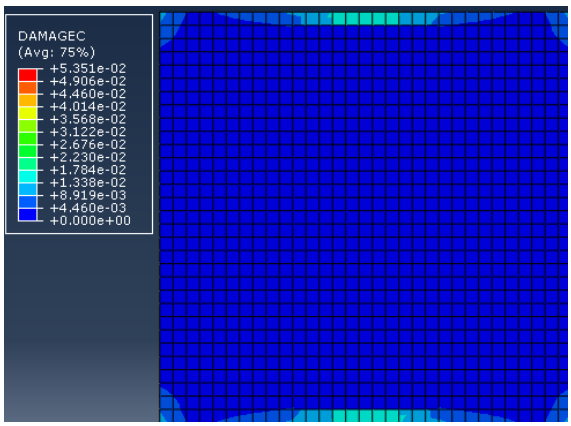
(b) Case8



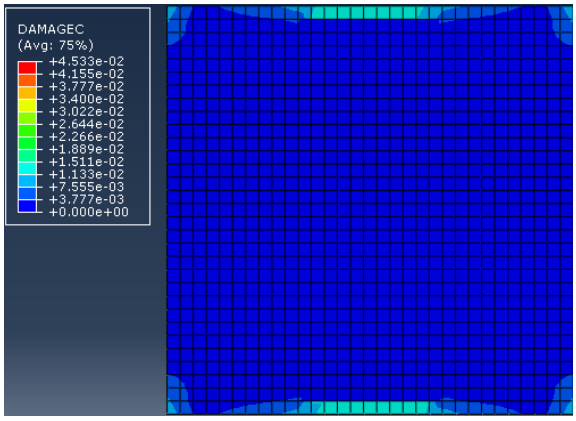
(c) Case 9



(d) Case 10

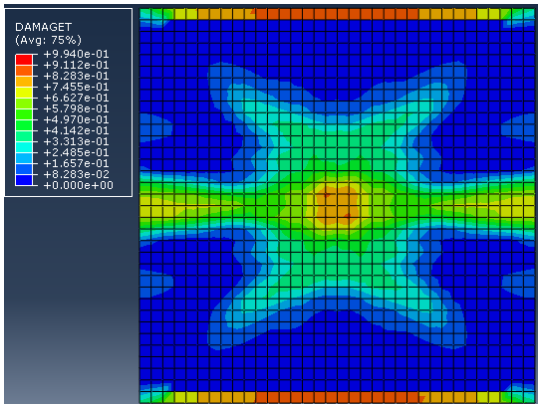


(e) Case 11

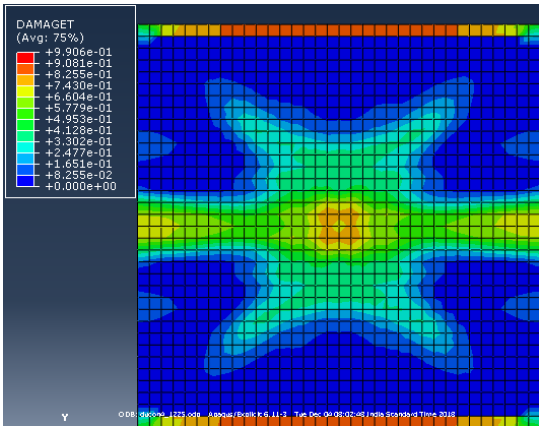


(f) Case 12

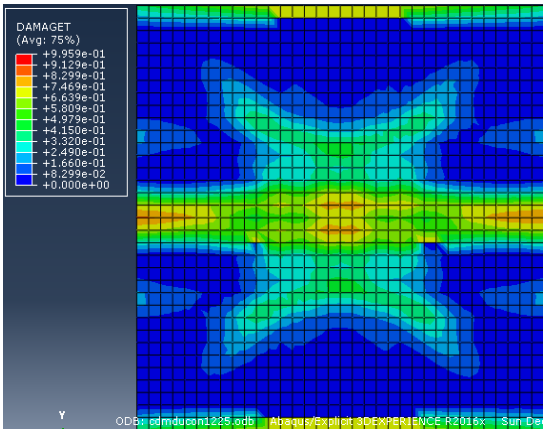
Figure 13 Distribution of compression damage variable for front jacket (t/D =0.3)



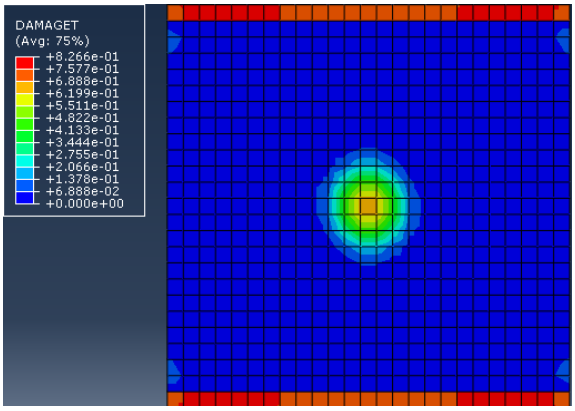
(a) Case 13



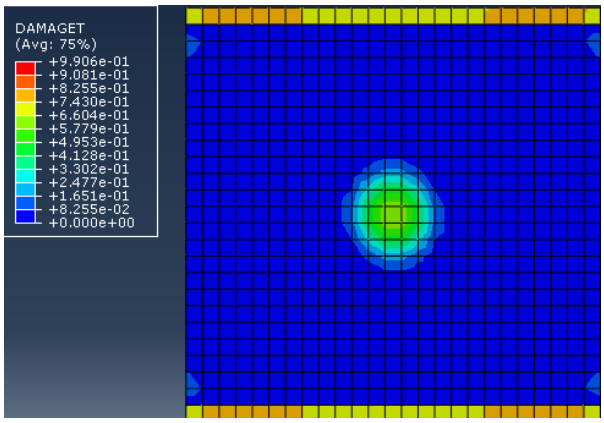
(b) Case14



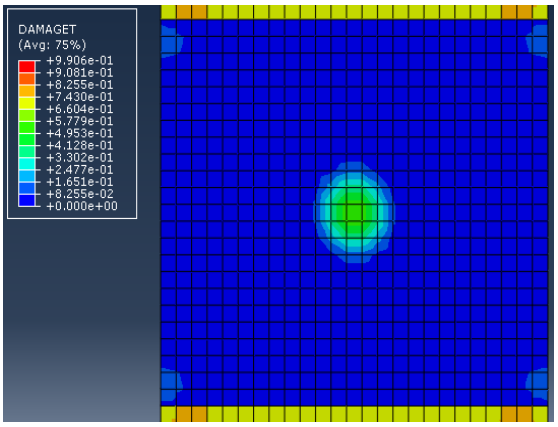
(c)Case 15



(d) Case 16

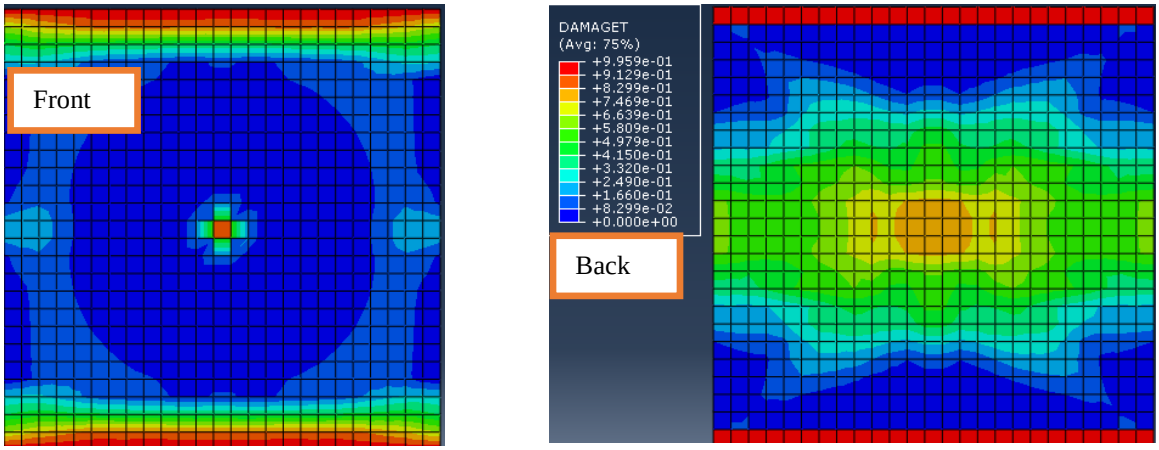


(e) Case 17

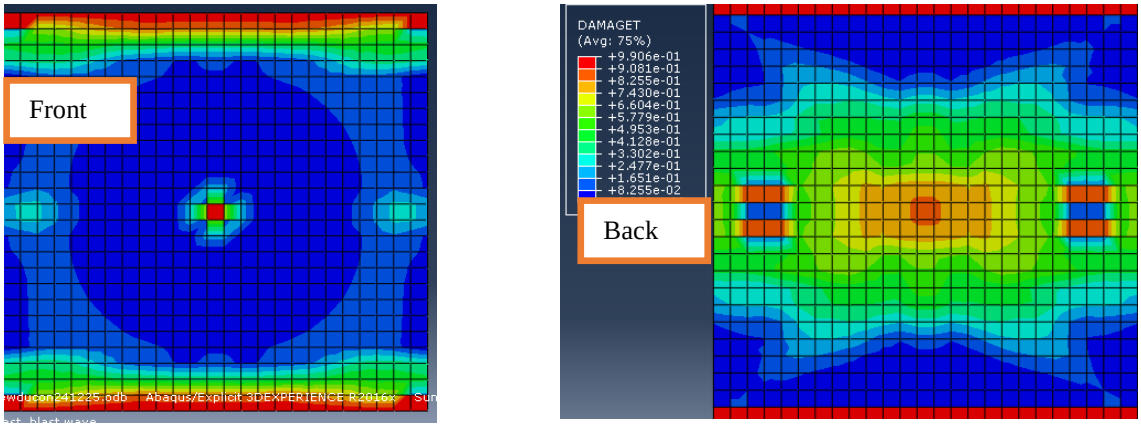


(f) Case 18

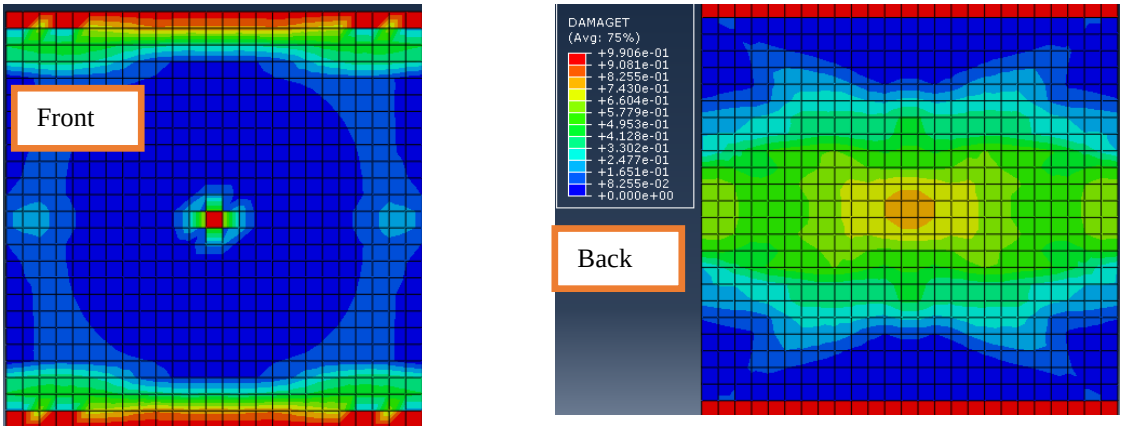
Figure 14 Distribution of Tensile Damage variable for RC panel(t/D = 0.5)



Case 16

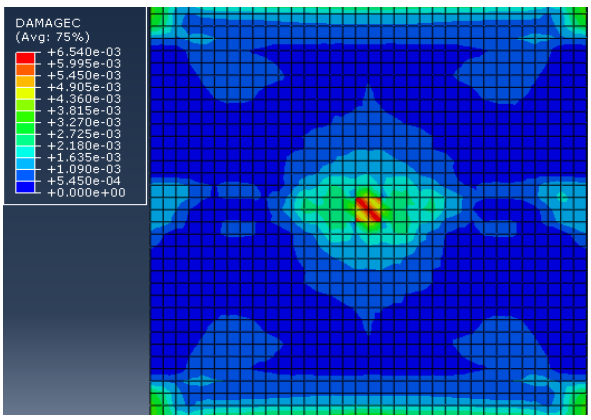


Case 17

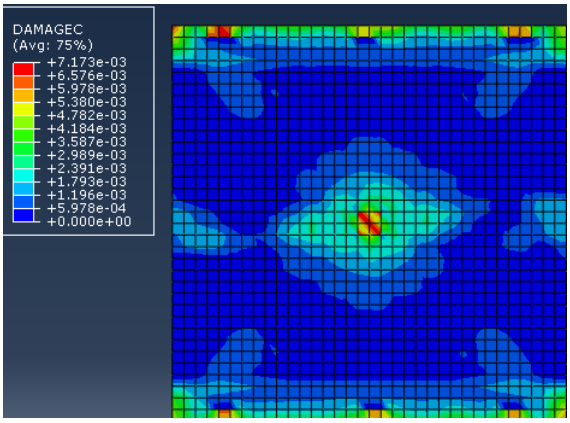


(e) Case 18

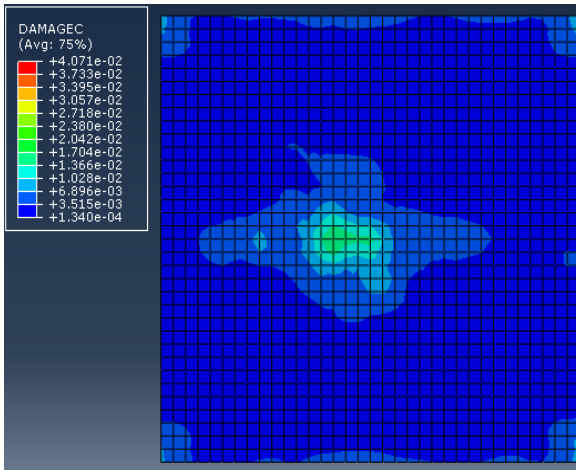
Figure 15 Comparison of Distribution of Tensile Damage variable for front and back jacket (t/D = 0.5)



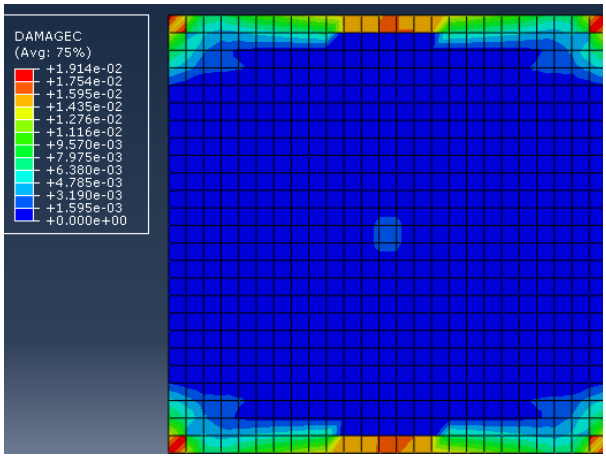
(a) Case 13



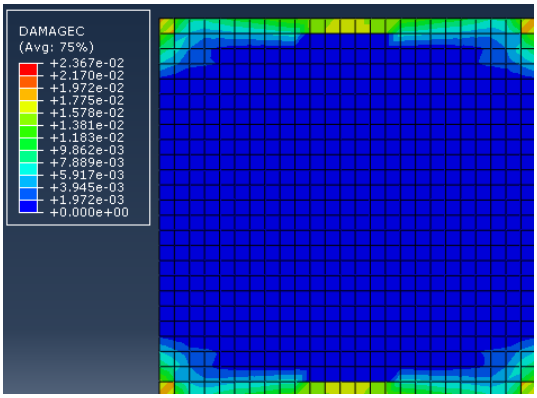
(b) Case 14



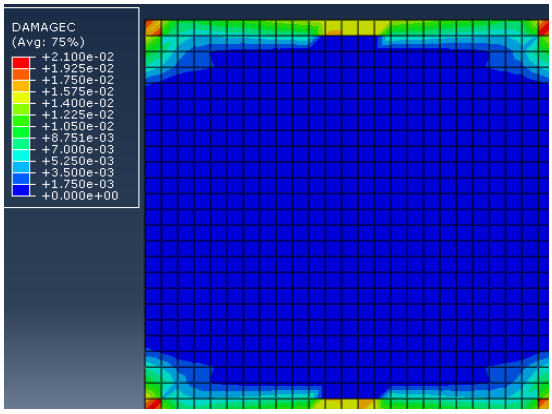
(c)Case 15



(d) Case 16



(e) Case 17



(f) Case 18

Figure 16 Distribution of compression damage variable for front jacket (t/D = 0.5)

IV. CONCLUSIONS

In the present study, the vertically positioned RC panel strengthened with SIMRC jacket under blast load scenario was analyzed using finite element method using ABAQUS application. The concrete damaged plasticity model was used to model behavior of concrete and grout of slurry infiltrated micro reinforced concrete. The linear kinematic hardening was taken into consideration for modelling reinforcement and wire mesh. The blast load was modelled using CONWEP function.

Results in terms of displacement time history indicate considerable reduction in displacement of SIMRC strengthened RC panel as compared to conventional RC panel without any protection. The SIMRC strengthened panel shows reduced damaged area as compared to conventional RC panel indicating the effectiveness of SIMRC under blast loading. The parametric study of performance of SIMRC strengthen RC panel under blast loading was carried out considering following parameters: (1) thickness ratio (t/D)(thickness of SIMRC jacket to thickness of RC panel (2)

RC panel protected by SIMRC jacket on single side or on both side, (3) Different percentage of wire mesh reinforcement. The results indicate that the displacement of RC panel with SIMRC jacket decreases with increase in thickness ratio (t/D) and with percentage increase in wire mesh reinforcement. The SIMRC jacket on both side of panel with maximum percentage of wire mesh reinforcement has maximum blast resistance capacity as reduced displacement and less damage area of panel as compared to single side jacketing. The damage pattern was studied using two damage variables i.e. tension and compression damage variable. The damage area of RC panel due to tensile cracking is more concentrated near support in case of panel with SIMRC jacket on both side. The failure of RC panel with SIMRC jacket is not affected by compression crushing.

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