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Modeling Steel Braces to Retrofit Concrete Structures Under the Impacts of Blast Loading

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Abstract
Over the past years, Iran has been subjected to terrorist and sabotage activities. Hence, it is critical to investigate the impacts of explosions on existing buildings nationwide. As we know, most buildings constructed in different area of the country are made of reinforced concrete due to the abundance and the economic viability of materials constituting concrete. For this, the goal of this study was to investigate and model steel braces to retrofit concrete structures subjected to blast loading. To demonstrate the accuracy of the modeling process, this study used an experimental study for validation and modeling results were found to be acceptable compared to experimental results; this indicated the efficiency of ABAQUS finite element software. The study also used a one-story, single-span reinforced concrete frame with a net height of three meters and the span length of four meters, as the frame was subjected to two different blast scenarios, one two meters from the left column and the other three meters from the center of the span on the ground surface. The scenarios were carried out in the form of three 10, 50, and 100 kg charges, and then the frame intended was reinforced by three types of steel X-, V-Chevron, and Inverted-V Chevron bracing. Later, various blast scenarios were examined. Analyses were performed at the time of 2.5 ms and the results demonstrated the good efficiency of using steel braces to retrofit reinforced concrete frames against blasts. Out of the used braces, V-Chevron and Inverted-V Chevron braces were found to have higher stability against blasts, while the X-bracing showed a greater level of energy absorption. Meanwhile, the results indicated the good stability of the braces at the time of 2.5 ms. The only weakness noted pertained to the way braces were connected to the frame, as damages were noted to have affected the braces.

Key words; reinforced concrete frame, steel brace, blast, steel X-brace, reinforced V-and Inverted-V Chevron

Introduction

Blasts at structures can cause severe damages and result in progressive and perfect failure. Pressures caused by blasts can vary based on the weight of explosives. This makes the design of structural elements under large explosions be impractical. Design engineers have always sought to introduce solutions to prevent failure caused by car blasts. From a structural design perspective, car explosions may be very important due to the large amounts of explosives detonated [1].

In 2015, Ghaffari comparatively investigated explosions at a reinforced concrete building and a reinforced concrete building retrofitted against lateral blast loading. He simulated his study in ABAQUS finite element software and demonstrated that the blasts on the ground varied in terms of detonation and distance. The findings revealed that the reinforced concrete building with bending frames had greater displacement and internal work, while having a lower base shear force compared to a composite structure [2].

In 2015, Golabi did a study to examine blasts in a reinforced concrete building. He also simulated this study in ABAQUS finite element software in 2-, and 3-D forms and investigated the likely damages caused by blasts. The findings showed that blasts first caused the local distribution of damages in a column close to the place of explosion, with other elements later affecting each other. He also stated that the damages caused by the blast depended on the amount of the explosive charge and the distance of the source of explosion from the structure [3].

In 2020, Kadhum investigated blasts in irregularly steel buildings and also in steel braced buildings. This study was conducted following terrorist attacks in Iraq in 2003. He did his study by simulation in ETABS software (2018) at different amounts of explosives. Findings revealed that the highest amounts of the displacement for the weights of 100, 350, and 700 kg explosives were noted in stories 6, 7, and 2, respectively [4]. This was followed by a work by Song (2020) who studied blast at steel frames. He did his study using logistic regression. Results from simulation indicated that the developed parametric fragility function to predict the possibility of structure failure caused by blast loading was a more accurate and applicable method compared to the simulation-based reliability [5].

Also, Yao et al. (2020) studied blasts and their effects in can-shaped structures. This study was subjected to an internal blast in a numerical and experimental way. This study also investigated the damages caused by blast and simulated failure states. The findings revealed that the numerical method well corresponded with the laboratory method in predicting fast failure states [6].

Mehdi Pour et al. (2020) investigated the retrofitting of steel braces under the effects of blast loading. For this study, they used the numerical and simulation methods in ABAQUS finite element software, which simulated a hospital structure frame. At first, they determined critical points in the intended frame. Based on previous results, it was noted that the retrofitting process could reduce stress [7].

In 2021, Zheng et al. did a study on steel composite structures and examined the effects of blast loading. They used the experimental and numerical method for their study. For this purpose, they provided a program along with the numerical method that fully confirmed the Eulerian method and used Lagrangian particles for materials [8].

A blast applies significant loads to a structure in a very short period. Thus, designing safe structures to counter blasts will be very much complicated and costly. Providing a safe design that produces the highest efficiency and the lowest costs will be possible only if there is accurate and sufficient knowledge about blasts and their impacts on structures, and also about the behavior of structures against loads applied; thus, this knowledge will be made possible by simulations. Because structure simulations are time-consuming and incur costs, they can only be examined through the non-linear dynamic analysis in a very short period. Under this situation, structures experience large deformation and the behavior of materials will be much different from the behavior of materials under conventional situations, due to the high rate of loading. Because of complex analyses, it is required to use software with special abilities. Analyzing a blast requires sufficient knowledge about the use of powerful software.

Over the past years, with the growing rate of terror attacks and blasts caused by explosives at buildings and relevant risks, various software has been introduced for simulation analyses, including ABAQUS finite element software, which specifically simulates structural blasts. Thus, the goal of the present stud was to investigate and model steel braces and retrofit concrete structures under the effects of blast loading.

Validation

To validate the ABAQUS finite element software, a credible article, which was performed by Li et al. in 2016, was investigated and modeled. They used a laboratory method to investigate blasts in a concrete slab reinforced with polymer fibers (Table 1).

Table 1: Mechanical characteristic of concrete (density, plasticity)

Parameter	Scale	Value
Density	ρ (kg/m^3)	**2400**
Young's modulus	E (N/m^2)	**19365*10^6**
Poisson's ratio	V	**0.2**
Eccentricity	E	**0.1**
Dilation angle	Ψ (degree)	**38**
Bulk modulus	K	**0.667**
$\frac{f_{b0}}{f_{c0}}$	-	**1.16**

The Johnson-Cook criterion was used to define longitudinal and transverse reinforcement steel chrematistics, as given by Table 2. For this, the Create Material section was used.

Table 2: Mechanical characteristics of define longitudinal and transverse reinforcement

Parameter	Scale	Value
Density	ρ (kg/m^3)	**7850**
Young's modulus	E (N/m^2)	**203000**
Poisson's ratio	V	**0.33**
Yield Stress constant	A (N/mm^2)	**304.330**
Strain hardening constant	B (N/mm^2)	**422.007**
	N	**0.345**
Viscous effect	C	**0.0156**
Thermal softening constant	M	**0.87**
Reference strain rate	$\dot{\varepsilon}_0$	**.0001 s^{-1}**
Melting temperature	θ_{melt} (K)	**1800**
Transition temperature	$\theta_{transition}$ (K)	**293**
	D_1	**0.1152**
	D_2	**1.0116**
Fraction strain constant	D_3	**-1.7684**
	D_4	**--0.05279**
	D_5	**0.5262**

After completing the analysis stages, the Result button was used to transfer to the Visualization environment in ABAQUS finite element software, and the results were examined.

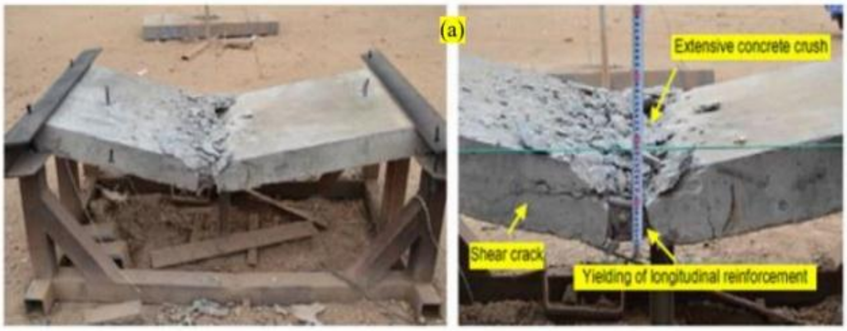

Figure 1: Concrete slab failure caused by blast using a laboratory method

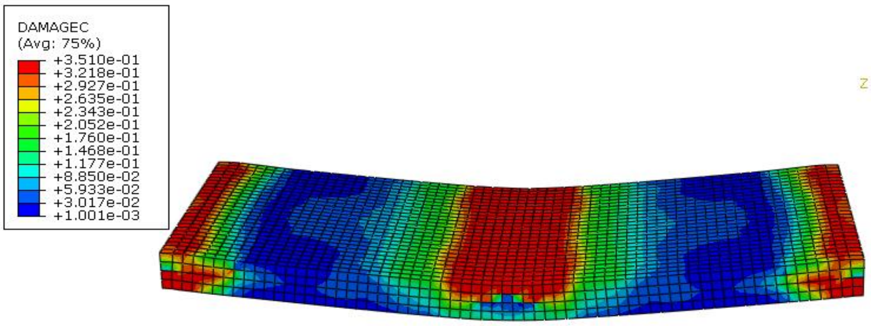

Figure 2: Pressure damage to the concrete slab caused by the explosion of 12 kg of TNT

A comparative investigation of modeling results in ABAQUS finite element method and blast results in the said article indicated that the modeling method was appropriate and the results were acceptable with a slight difference. The reason for the difference between the modeling and the article results was due to the size of a mesh and the input data related to mechanical characteristics.

Methodology

In this model, the model studied is a reinforced concrete frame retrofitted with steel braces. The studied frame is a single-span and single-story frame whose column heights just under the beam measured three meters while its span length was four meters. The studied model is seen in the figure below.

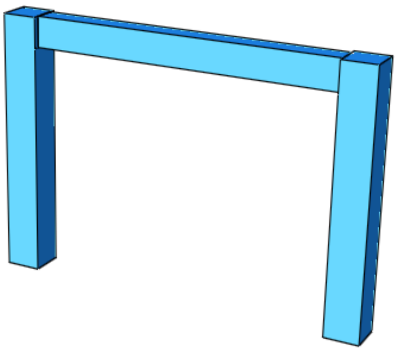

Figure 3: Geometric model of the studied frame

The model studied is made of several separate elements, including two columns and a solid concrete beam, wired longitudinal and transverse rebars, steel braces, and steel plates of solid brace connections.

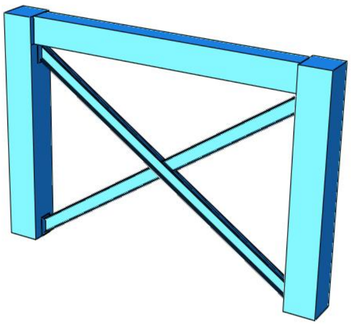

Figure 4: Frame model with X-bracing

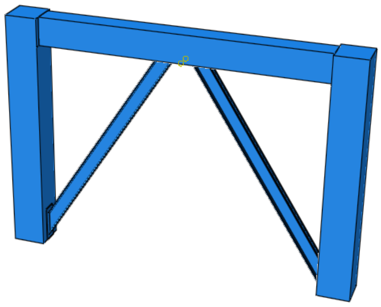

Figure 5: Frame model with Inverted-V bracing

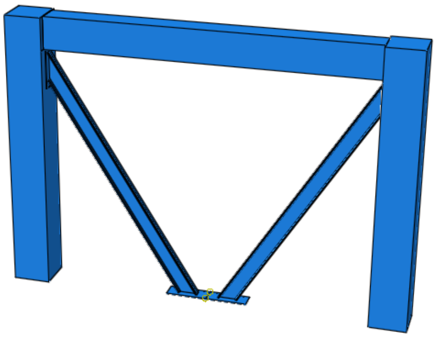

Figure 6: Frame model with V-bracing

Table 3: Studied frame model

Frame	Parameter
No-bracing frame	F_1
X-bracing frame	F_2
Inverted-V bracing frame	F_3
V-bracing frame	F_4

Table 4: Place of explosives-horizontal distance from Column L

Horizontal distance (m)	Parameter
Two meters from the side of the left column	L_1
Three meters from the middle of the span	L_2

Table 5: Place of explosives- vertical distance from the foot of Column h

Vertical distance (m)	Parameter
On the ground surface	H

Table 6: Weight of explosives M

Weight of TNT explosives (Kg)	Parameter
10	M_1
50	M_2
100	M_3

Table 7: Blast models

Blast models	Blast model characteristics		
	Frame model F	**Horizontal height (L) (m)**	**Weight of explosives (M) (Kg)**
$F_1L_1M_1$	No-bracing frame	Two meters from the side of the left column	10
$F_1L_1M_2$	No-bracing frame	Two meters from the side of the left column	50
$F_1L_1M_3$	No-bracing frame	Two meters from the side of the left column	100
F_1L_2M1	No-bracing frame	Three meters from the middle of the span	10
$F_1L_2M_2$	No-bracing frame	Three meters from the middle of the span	50
$F_1L_2M_3$	No-bracing frame	Three meters from the middle of the span	100
$F_2L_1M_1$	X-bracing frame	Two meters from the side of the left column	10
$F_2L_1M_2$	X-bracing frame	Two meters from the side of the left column	50
$F_2L_1M_3$	X-bracing frame	Two meters from the side of the left column	100
$F_2L_2M_1$	X-bracing frame	Three meters from the middle of the span	10
$F_2L_2M_2$	X-bracing frame	Three meters from the middle of the span	50
$F_2L_2M_3$	X-bracing frame	Three meters from the middle of the span	100
$F_3L_1M_1$	Inverted-V bracing frame	Two meters from the side of the left column	10
$F_3L_1M_2$	Inverted-V bracing frame	Two meters from the side of the left column	50
$F_3L_1M_3$	Inverted-V bracing frame	Two meters from the side of the left column	100
F_3L_2M1	Inverted-V bracing	Three meters from the	10

	frame	middle of the span	
$F_3L_2M_2$	Inverted-V bracing frame	Three meters from the middle of the span	50
$F_3L_2M_3$	Inverted-V bracing frame	Three meters from the middle of the span	100
$F_4L_1M_1$	V-bracing frame	Two meters from the side of the left column	10
$F_4L_1M_2$	V-bracing frame	Two meters from the side of the left column	50
$F_4L_1M_3$	V-bracing frame	Two meters from the side of the left column	100
F_4L_2M1	V-bracing frame	Three meters from the middle of the span	10
$F_4L_2M_2$	V-bracing frame	Three meters from the middle of the span	50
$F_4L_2M_3$	V-bracing frame	Three meters from the middle of the span	100

Findings

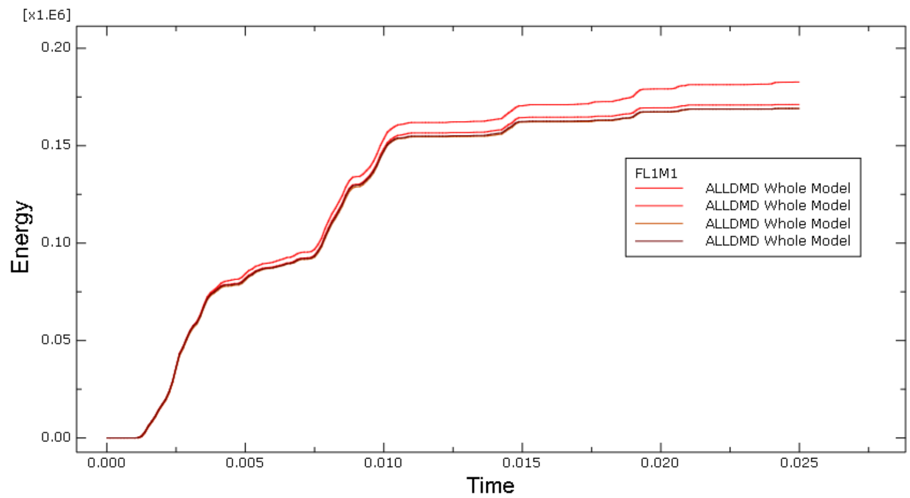

Figure 7: Comparison of energy loss caused by damage in models $F_1L_1M_1$, $F_2L_1M_1$, $F_3L_1M_1$, and $F_4L_1M_1$

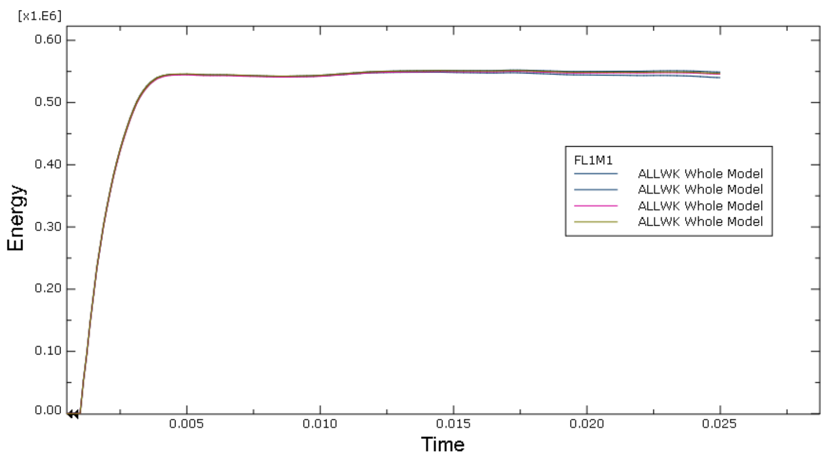

Figure 8: Comparison of the energy of work done in models $F_1L_1M_1$, $F_2L_1M_1$, $F_3L_1M_1$, and $F_4L_1M_1$

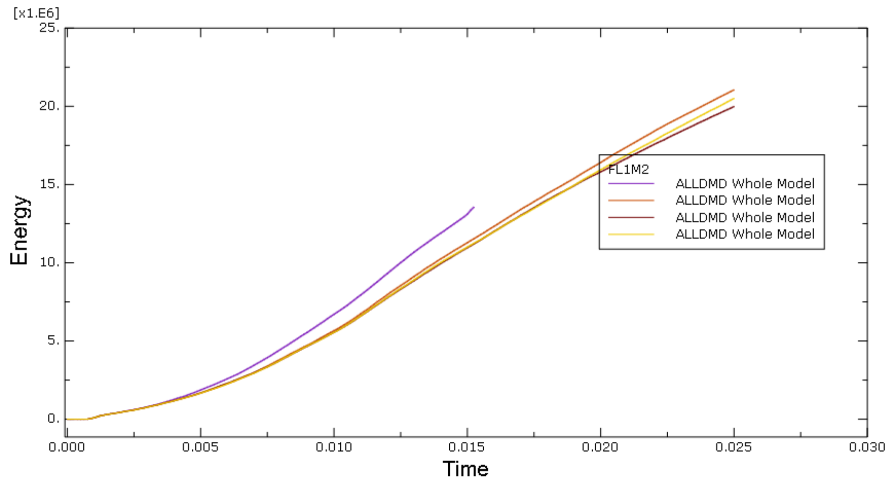

Figure 9: Comparison of energy loss caused by damage in models $F_1L_1M_2$, $F_2L_1M_2$, $F_3L_1M_2$, and $F_4L_1M_2$

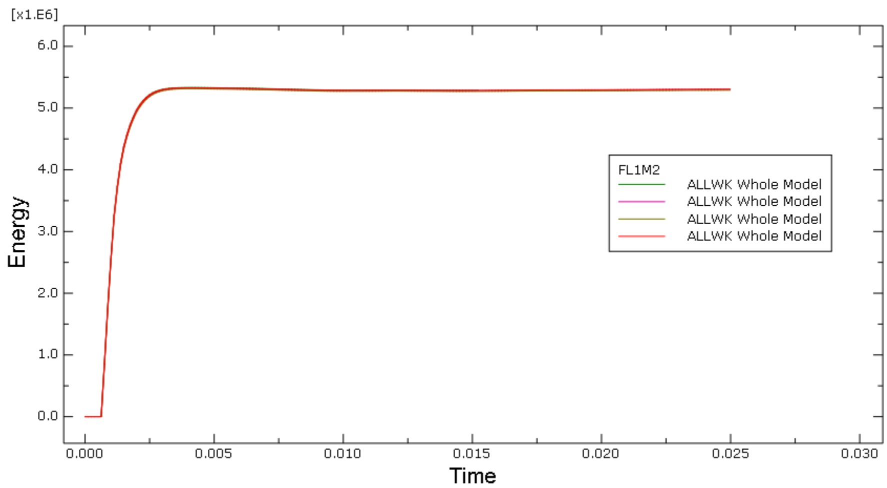

Figure 10: Comparison of the energy of work done in models $F_1L_1M_2$, $F_2L_1M_2$, $F_3L_1M_2$, and $F_4L_1M_2$

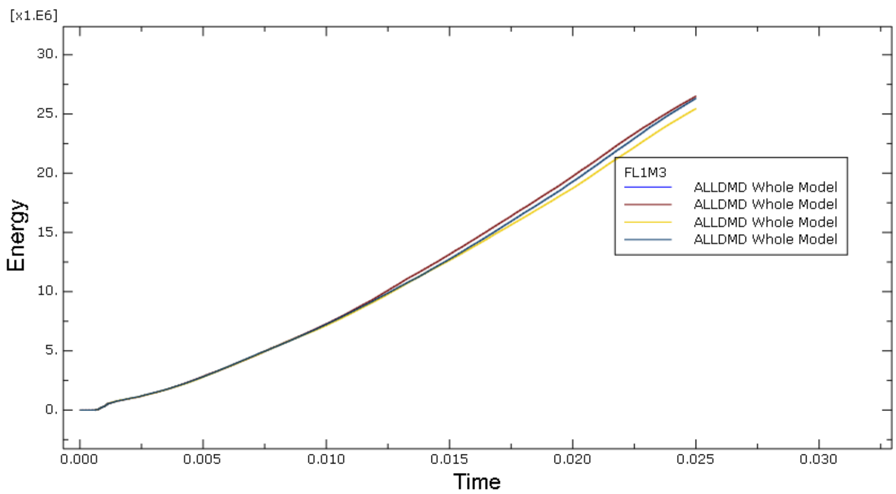

Figure 11: Comparison of energy loss caused by damage in models $F_1L_1M_3$, $F_2L_1M_3$, $F_3L_1M_3$, and $F_4L_1M_3$

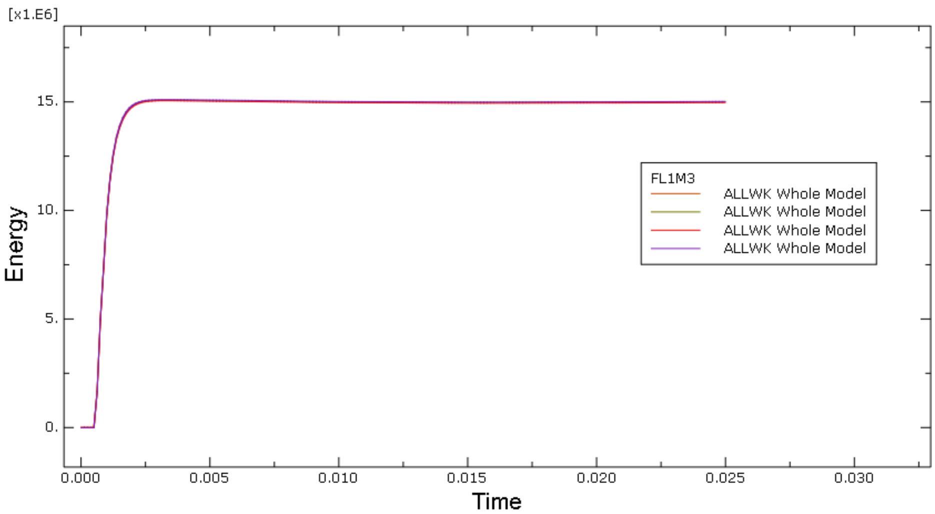

Figure 12: Comparison of the energy of work done in models $F_1L_1M_3$, $F_2L_1M_3$, $F_3L_1M_3$, and $F_4L_1M_3$

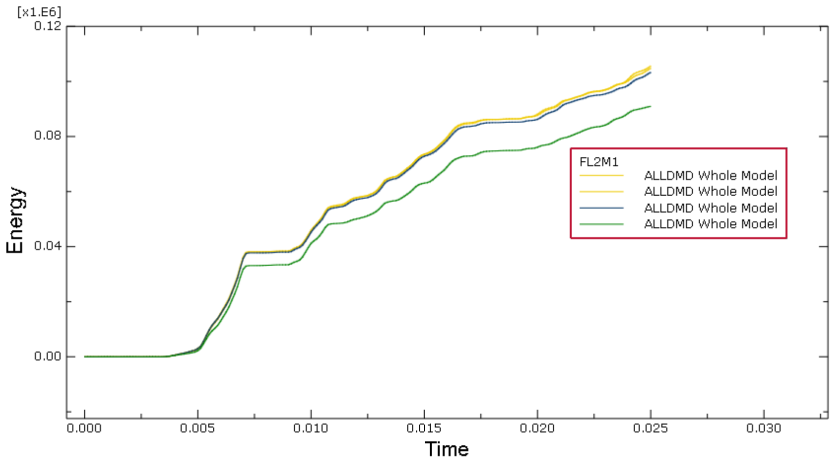

Figure 13: Comparison of energy loss caused by damage in models $F_1L_2M_1$, $F_2L_2M_1$, $F_3L_2M_1$, and $F_4L_2M_1$

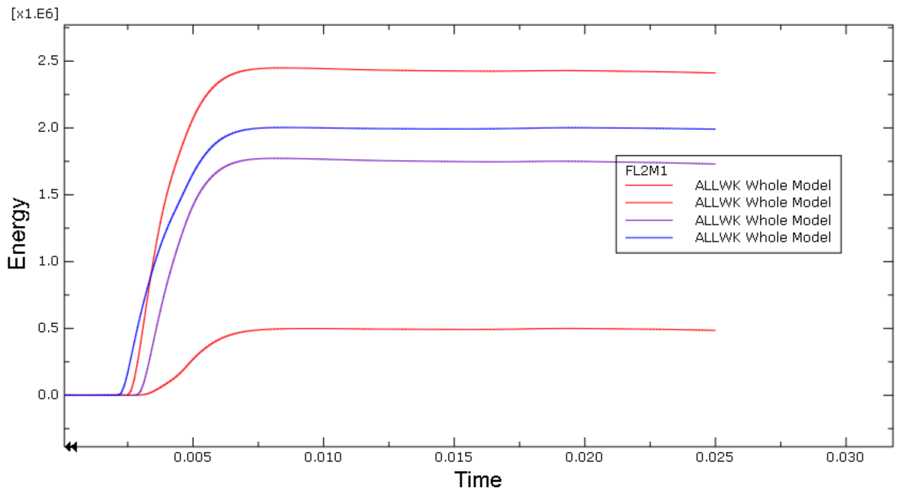

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Figure 14: Comparison of the energy of work done in models $F_1L_2M_1$, $F_2L_2M_1$, $F_3L_2M_1$, and $F_4L_2M_1$

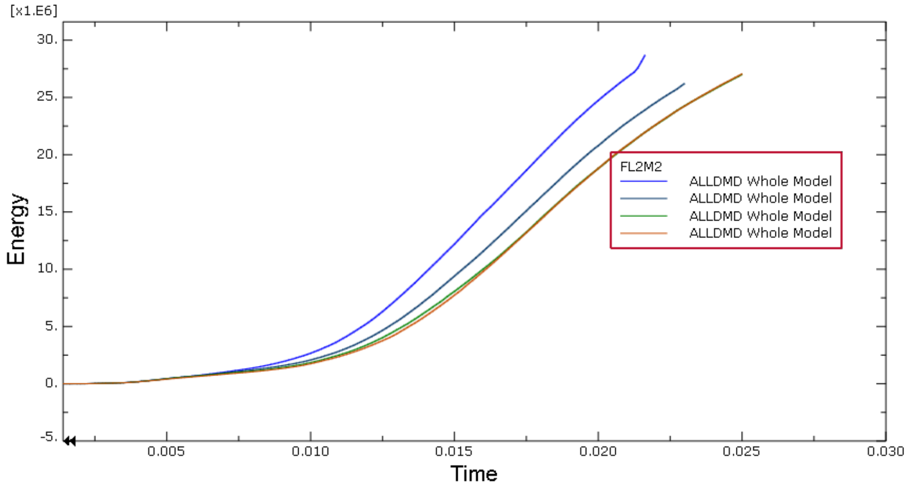


Figure 15: Comparison of energy loss caused by damage in models $F_1L_2M_2$, $F_2L_2M_2$, $F_3L_2M_2$, and $F_4L_2M_2$

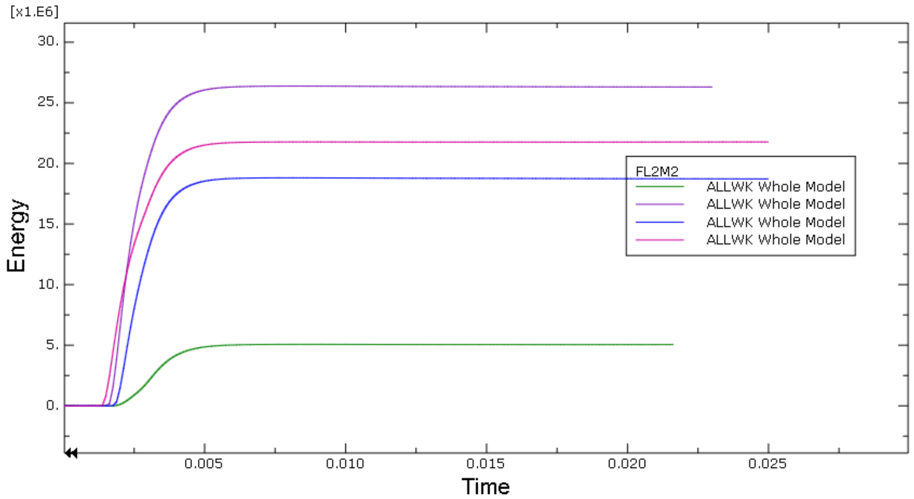


Figure 16: Comparison of the energy of work done in models $F_1L_2M_2$, $F_2L_2M_2$, $F_3L_2M_2$, and $F_4L_2M_2$

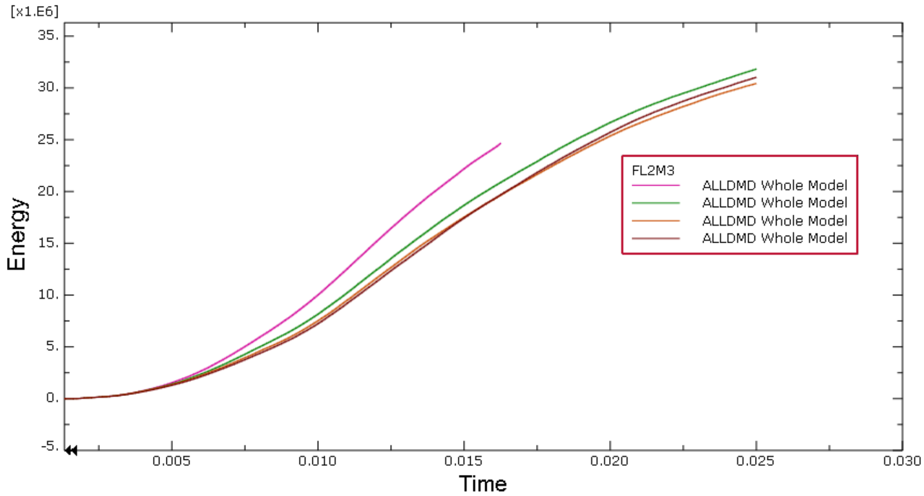


Figure 17: Comparison of energy loss caused by damage in models $F_1L_2M_3$, $F_2L_2M_3$, $F_3L_2M_3$, and $F_4L_2M_3$

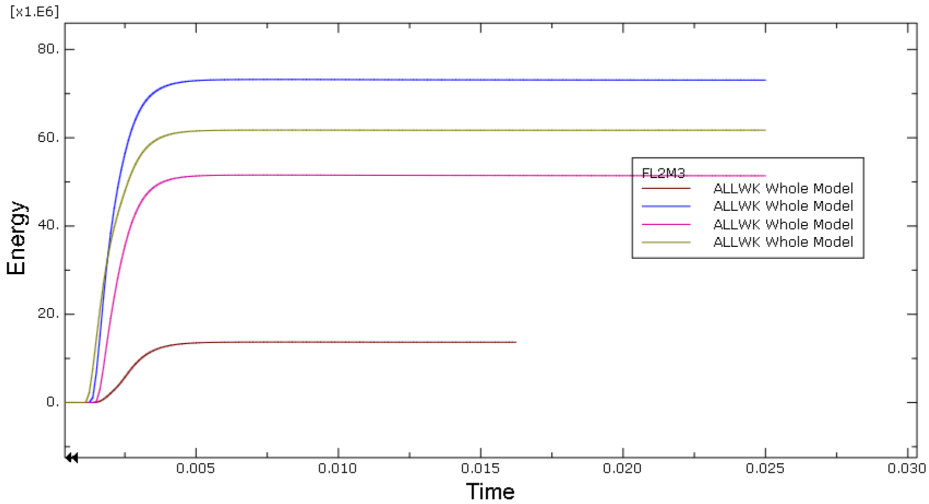
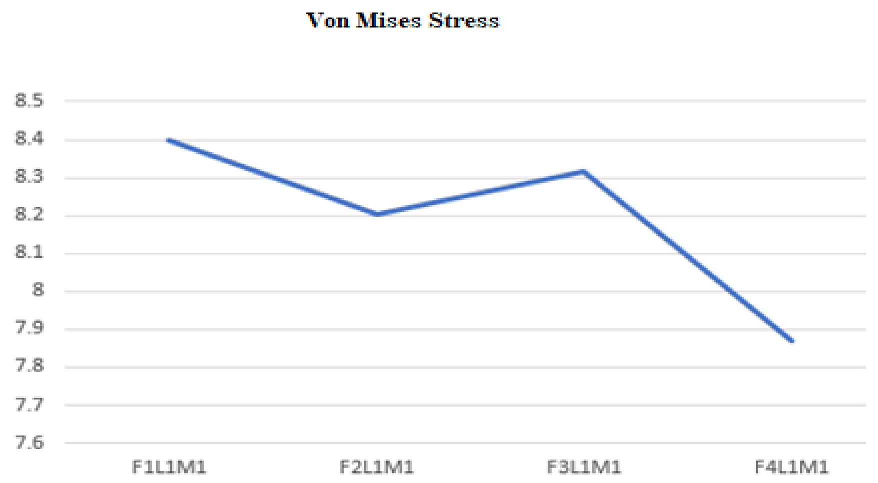


Figure 18: Comparison of the energy of work done in models $F_1L_2M_3$, $F_2L_2M_3$, $F_3L_2M_3$, and $F_4L_2M_3$

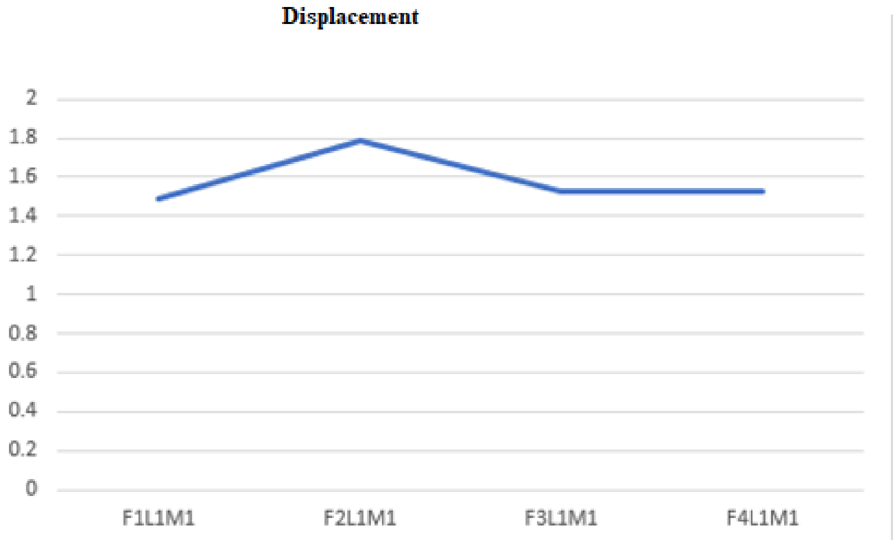
Table 9: Values and outputs extracted from various blast scenarios

Blast model	Blast model characteristics									
	Stress	**Displacement**	**Acceleration**	**Support reaction**	**Plastic strain**	**Pressure damage**	**Tensile damage**	**Energy loss**	**Energy of work done**	**Time (ms)**
F1L1 M1	8.397	1.488	3.418e7	1.269 e4	3.373 e-3	2.313e -2	9.538 e-1	0.175 e6	0.55e 6	2.5
F1L1 M2	3.859e 7	4.905e1	7.182e14	2.94e 4	2.262 e4	3.51e- 1	9.538 e-1	14e6	5.5e6	1.5 3
F1L1 M3	4.938e 1	2.62	1.688e8	1.445 e5	1.144 e-2	3.276e -1	9.538 e-1	0.62e 6	13e6	1.2 5
F1L2 M1	2.098e 1	6.618	1.261e6	4.911 e4	9.912 e-4	2.024e -3	9.538 e-1	0.1e6	0.5e6	2.5
F1L2 M2	1.774e 9	5.596e1	1.941e14	5.397 e4	1.104 e5	3.51e- 1	9.538 e-1	30e6	5e6	2.1 7
F1L2 M3	6.095e 15	5.965e1	1.035e9	5.328 e4	4.499 e-1	3.51e- 1	9.538 e-1	25e6	13e6	1.6 4
F2L1 M1	8.202	1.789	1.75e7	1.196 e4	3.306 e-3	2.206e 2	9.538 e-1	0.175 e6	0.55e 6	2.5
F2L1 M2	2.962e 1	1.116	2.967e8	3.754 e4	5.64e -2	3.51e- 1	9.538 e-1	22e6	6e6	2.5
F2L1 M3	3.338e 1	1.598e1	2.734e8	4.267 e4	5.505 e-2	3.510e -1	9.538 e-1	27e6	15e6	2.5
F2L2 M1	1.339e 2	0.452	1.245e6	5.078 e4	1.144 e-3	2.046e -3	9.538 e-1	0.1e6	2.5e6	2.5
F2L2 M2	1.562e 6	4.669e1	2.299e13	4.42e 4	3.774 e-1	3.51e- 1	9.538 e-1	27e6	27e6	2.5

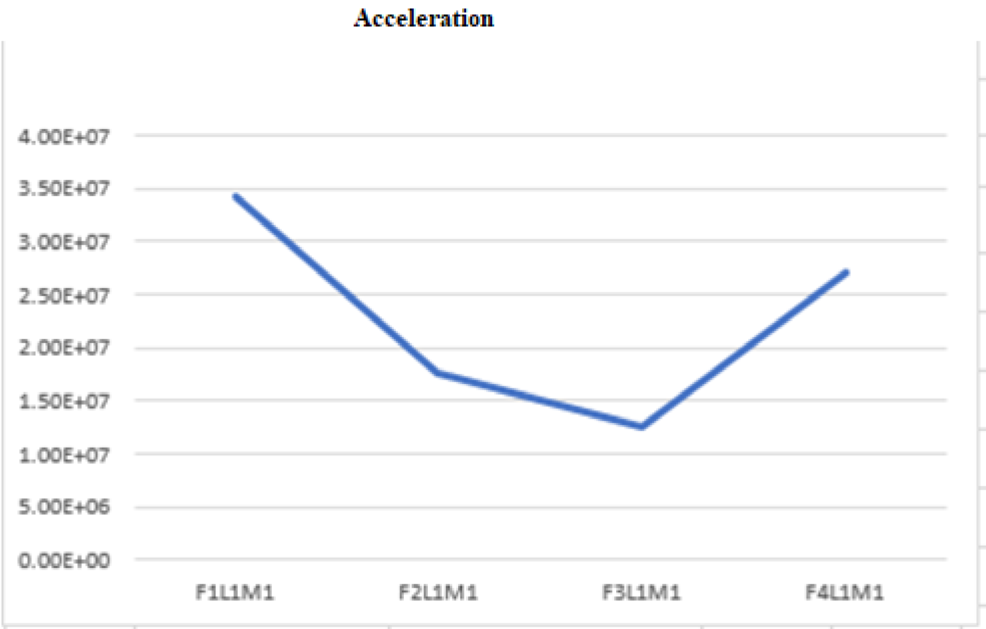
F2L2 M3	2.909e 2	5e1	4.323e8	6.311 e4	5.853 e-2	3.51e-1	9.538 e-1	35e6	80e6	2.5
F3L1 M1	8.316	1.532	1.294e7	1.197 e4	2.176 e-2	9.538-1	9.538 e-1	0.2e6	0.6e6	2.5
F3L1 M2	2.803e 1	1.124e1	3.224e8	2.944 e4	6.176 e-2	3.51e-1	9-538e-1	20e6	6e6	2.5
F3L1 M3	2.796e 1	1.772e1	3.18e8	5.505 e4	7.592 e-2	3.51e-1	9.538 e-1	26e6	15e6	2.5
F3L2 M1	7.554e 1	5.54	1.36e6	5.105 e4	1.138 e-3	2.008e -3	9.538 e-1	0.1e6	1.75e 6	2.5
F3L2 M2	1.879e 2	2.881e1	2.263e8	4.977 e4	4.247 e-2	3.51e-1	9.538 e-1	30e6	20e6	2.5
F3L2 M3	2.505e 2	4.584e1	1.964e8	6.218 e4	4.655 e-2	3.51e-1	9.538 e-1	31e6	50e6	2.5
F4L1 M1	7.871	1.532	2.701e7	1.199 e4	3.301 e-3	2.197e -2	9.835 e-1	0.18e 6	0.6e6	2.5
F4L1 M2	2.664e 1	1.051e1	3.026e8	2.991 e4	6.234 e-2	3.51e-1	9.538 e-1	20e6	5.5e6	2.5
F4L1 M3	2.742e 1	1.632e1	2.512e8	4.502 e4	6.125 e-2	3.51e-1	9.835 e-1	27e6	15e6	2.5
F4L2 M1	2.337e 1	5.342	1.251e6	5.121 e4	1.084 e-3	1.902e -3	9.538 e-1	0.09e 6	2e6	2.5
F4L2 M2	1.058e 2	3.676e1	2.293e8	4.778 e8	3.111 e-2	3.51e1	9.538 e-1	30e6	25e6	2.5
F4L2 M3	1.39e2	4.345e1	2.018e8	3.479 e-4	5.617 e-2	3.51e-1	9.538 e-1	32e6	60e6	2.5



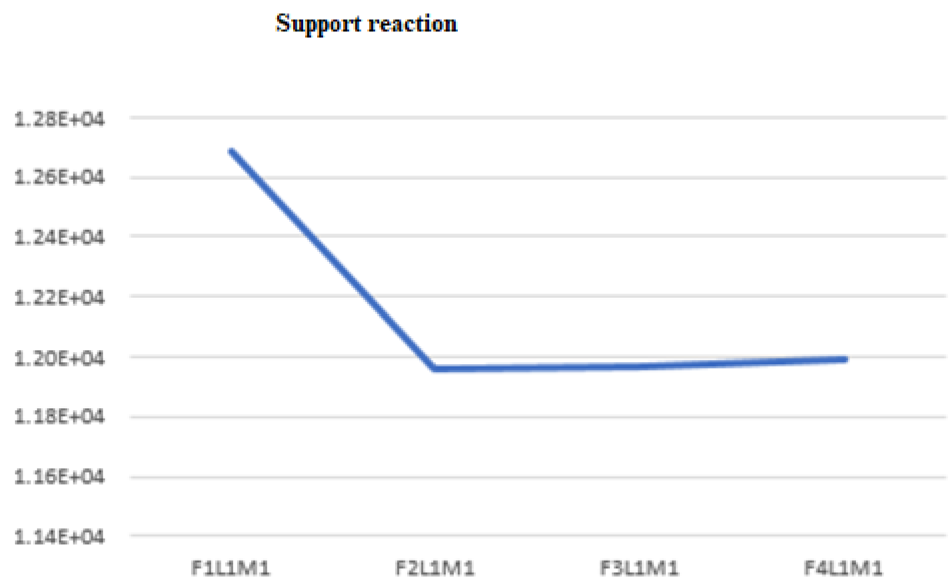
Von Mises stress for 10 kg of explosives in different scenarios



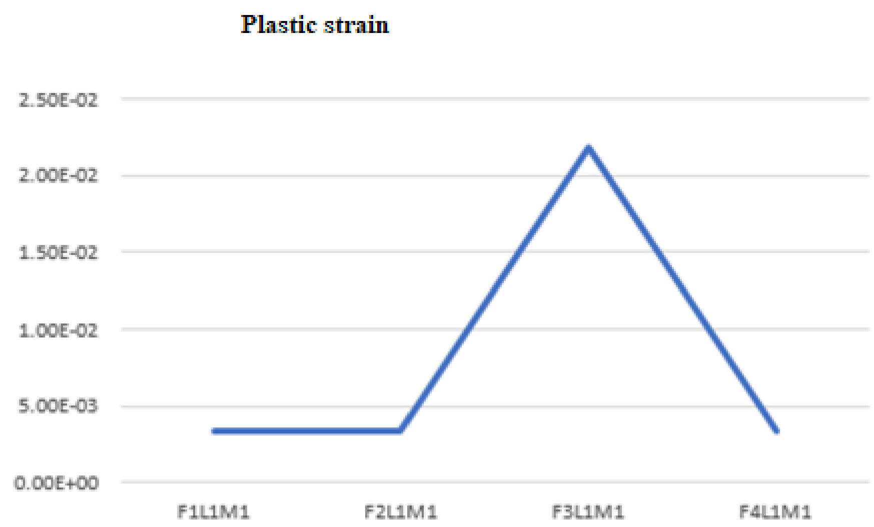
Displacement for 10 kg of explosives in different scenarios



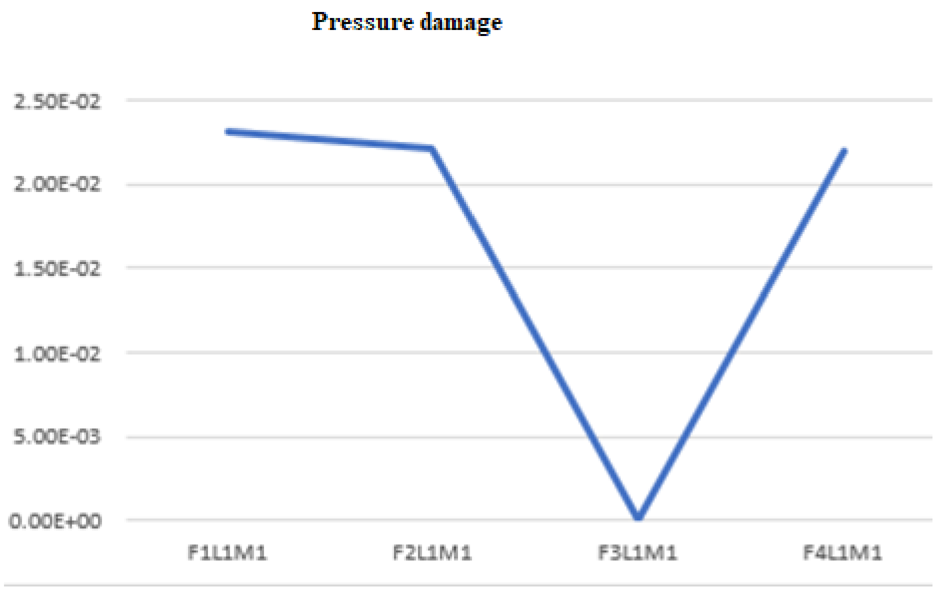
Acceleration for 10 kg of explosives in different scenarios



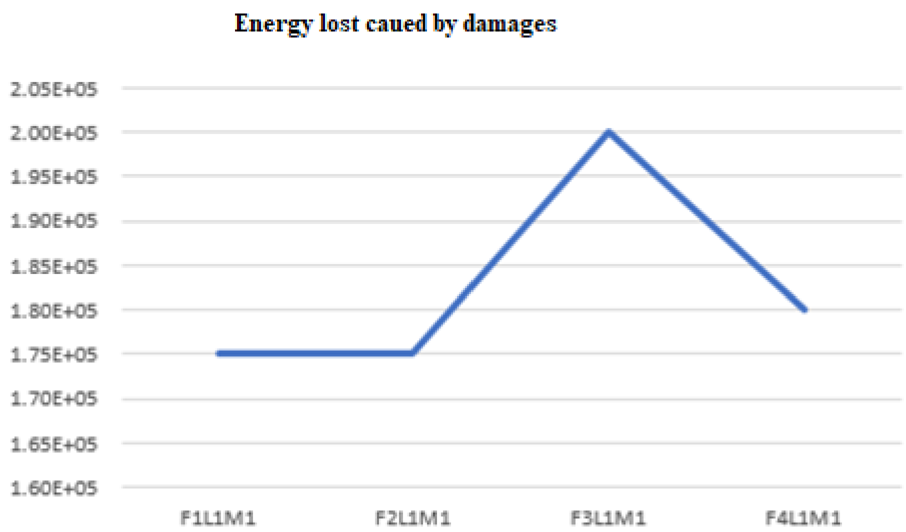
Support reaction for 10 kg of explosives in different scenarios



Plastic strain for 10 kg of explosives in different scenarios



Pressure damage for 10 kg of explosives in different scenarios



Damaged-caused energy loss for 10 kg of explosives in different scenarios

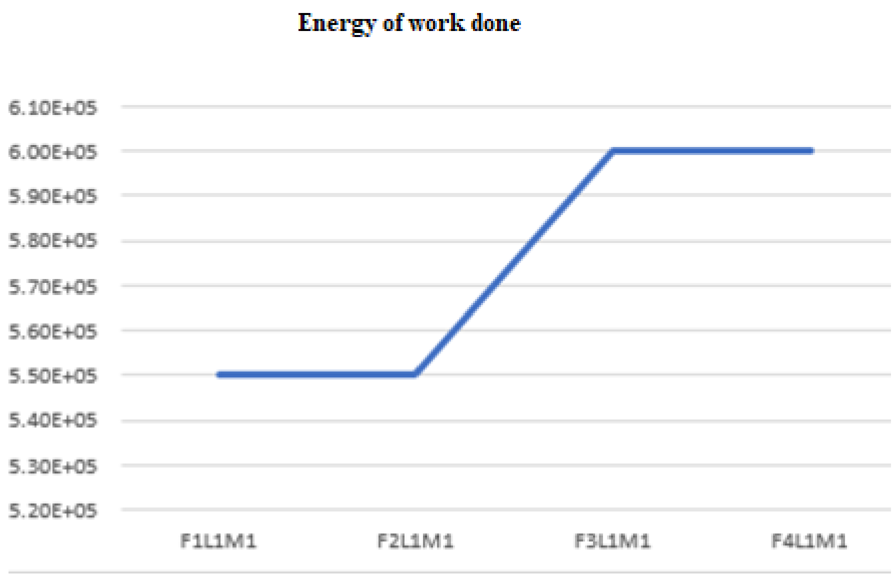


Figure 19: The amount of energy of work done, von Mises stress, displacement, acceleration, support reaction, plastic strain, pressure damage, energy loss for 10 kg of explosives under different scenarios

Conclusion

Blasts occurred under various scenarios and the time of 2.5 ms was considered for the conduct of modeling and the application of blasts of various weights. The results suggested that the model without bracing could face failure at a time of less than 2.5 ms and the analysis process could stop. However, after adding steel braces to the concrete frame model, the analysis process continued until the intended time of 2.5 ms. According to various blast scenarios, it was noted that the stress created significantly decreased after placing steel braces, with the V-bracing model causing less stress.

According to the displacement caused by the blast that occurred two meters from the column in the model without steel bracing, the column was found to have less ability to resists displacement, which decreased after adding steel brace, with the brace controlling for the displacement created.

According to the acceleration caused by the blast in the studied models, the acceleration caused by the model without bracing was found to be very high, which decreased after steel braces were added. As for the explosion two meters from the column, it was noted that the addition of steel braces to the model significantly decreased support reaction compared to the geometric model without braces.

According to various blast scenarios, the addition of steel bracing to concrete frames increased plastic strain and helped the structure to resist larger amounts of loads applied. According to the findings of the various blast scenarios, the level of pressure damages in the model caused by the inverted-V Chevron bracing was lower. It was also noted that the addition of steel bracing could increase structural stability against the application of blast loads, with the V- and inverted-V Chevron braces having higher abilities in this connection. The addition of steel braces to the reinforced concrete frame significantly increased the energy absorbed by the structure as a result of the blast loads applied.

The highest rates of stress, displacement, and damages caused in the model without bracing were noted in the upper parts of the columns and the beams. The addition of steel braces caused greater amounts of stress and displacement in the brace compared to the entire structure, with the beam also seeing greater amounts of stress and displacement. The damages caused to the structure started from the foot of the column and spread to other parts of the structure. The damages from the blast in the studied structure were caused by the weak concrete tension, which resulted in the structural stability increasing after the addition of steel braces. Out of the used bracing models, the X-bracing demonstrated a greater ability of energy absorption.

The addition of a steel brace to the reinforced concrete frame increased stability, with the only weakness of this coming from the connection points of the braces, which were placed by a prong and a steel plate inside the concrete; however, the impacts of the pressure of the loads applied caused damages to the prong connections and the steel plate, thereby resulting in damages to the structure.

As for the fixed-charge scenario, damages caused by the blast in front of the structure were found to be greater than those in the side of the structure. As noted from the findings of the various blast scenarios, with the increase of explosive charges in the explosion source, the pressure of the blast load also increased, resulting in the increased damages and other parameters, including stress and strain in the structure.

Also, consistent with various scenarios, the place of explosion was much important than to the structure, and the closer the blast to structural elements, the greater the loads applied to the structure as a result of the blast, thereby inflicting more damages to the structure. Findings helped us to have better insight into structures subjected to blasts. Validation findings also revealed that the model of materials, the explosive load parameters, and the way explosive loads were applied to the structure revealed good convergence with the works of other researchers, suggesting the greater efficiency of the ABAQUS finite element software.

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