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RESEARCH PAPER

Evaluation of Seismic Designed Pipe Racks under Accidental Explosions with Finite Element Method

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ABSTRACT: The safety of pipe racks in petrochemical sites or refineries needs to be considered to ensure a sustainable productivity and explosions would make these structures vulnerable. Non-building structures field have remained relatively intact in comparison with ordinary buildings for which state-of-the-art guidelines are regularly proposed and existing ones are renewed. To have comprehensive knowledge on non-building structures response to blast load, multiple factors are involved. This paper pinpoints how these variables affect the pipe racks and for this purpose, ABAQUS software undertakes the solving process as multi-degree of freedom (MDOF) and Finite Element method are required. Despite ordinary buildings, pipe racks are accompanied by non-structural components whose effects in design are evaluated not significant. Moreover, adequacy and accuracy of usual analysis including static and non-linear dynamic analysis are investigated. According to the calculations, static analysis is highly sensitive to irregularities and blast duration, therefore, it may lead to invalid results. Finally, a consequence analysis is suggested to be a contribution to engineers for outlining a well-arranged layout for different sectors.

Keywords: Blast Resistant Structures, Dynamics of Structures, FEM.

1. Introduction

In this era, the industrial productivity of most countries is highly dependent on oil-process facilities. The first successful oil extraction took place in Pennsylvania (1859) and since then, groundbreaking researches as well as new tools have facilitated the extraction and post-extraction mechanisms. This undoubtedly has a long way ahead to go because unprecedented environmental conditions or immeasurable probabilities of accidents alongside human errors make the re-investigation of design principles invaluable. This may be more of an importance for oil-led economies where raw oil or the export of the processed material constitutes a remarkable share of the annual budget. On the one hand, the related infrastructures should be designed resistant to routine loads. On the other hand, the supply chain should remain operational to a logic level for natural or accidental. In many regions inside the Middle East, the critical load is earthquake (Syed et al.,

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2017). So decades-long researches have been made to assess the performance of residential buildings in the face of earthquakes or, occasionally, blasts. For example, ACI-base-designed buildings were subjected to scrutiny with various explosion scenarios to verify the credibility of seismic design (Chiranjeevi and Simon, 2016; Syed et al., 2017).

Such studies have been carried out abundantly for buildings but much less in the case of non-building structures (Chiranjeevi and Simon, 2016). At the same time, the probability of explosion is high in refineries. The blasts may be triggered by external stimuli or accidents; for example, in an earthquake where the tremors may cause leakage and subsequently combustion (Kidam and Hurme, 2013; Planas et al., 2015; Suzuki, 2008). Accidents in the sites may also happen recurrently as a repercussion of a low safety culture (Aquino-Gaspara et al., 2021) and this situation may get exacerbated when coupling effect of blast wave and fragment would start a domino accident (Lai et al., 2021). Considering pipe racks vulnerable more than other sectors of a petrochemical site is not a faulty premise since among 364 accidents in specified petrochemical sites, pipe systems and racks were reported as repeatedly affected structures (Kidam and Hurme, 2013).

In the above-mentioned sites, three main categories can be observed: buildings, non-building structures, and non-building structures similar to buildings (ASCE, 2011; ISDPF, 2016). The latest was introduced at 1988 in UBC and improved by today in later revisions (Drake, 2004). Pipe racks are discerned as one of the best-known members of the non-building structures family (ASCE, 2011; Bedair, 2015; ISDPF, 2016). However, these advances have not been enough in comparison with those of ordinary buildings although a vast variety of daily-life demands, including clean water, electricity and sewage discharge, are feasible when pipe racks operate (Horold et al., 2000). Engineers often exploit buildings guidelines to design pipe racks. This approach not only may be non-conservative but also put the structures at serious risk. As an instance, the performance of the buildings frequently is defined due to life-safety or collapse prevention. Nevertheless, non-building structures based on their utilization status might not be allowed to reach a yield state (Horold et al., 2000). Furthermore, neither the nature of loads nor the occupation condition resembles residential buildings (Moharrami et al., 2015). The main role of racks is the distribution of pipes between levels and engaged parts in a facility. The conveyed pipes can

Significantly influence the stress distribution, deformation values and period of racks in seismic design (Roodpeyma and Mahmoudzadeh Kani, 2021). Also, previous researches confirm a 20% reduction in material consumption when the pipes are modeled simultaneously (Shahiditabar and Mirghaderi, 2013). In contrast with seismic analysis, the explosion analysis not only would be time-consuming but challenging, especially when it comes to details. CFD, coupled with competence in interpretation, is likely to end up with precise results, but the hardship in this path convinces engineers to take advantage of TNO, Baker-Sterlo or TNT equivalent dimensionless graphs (Hansen et al., 2010) . The selection of explosion type, affecting the structures in refineries, varies as the source of blast changes. It is commonly believed that vapor cloud explosions constitute the major cause of on-site blasts (ASCE, 2006). Far-field explosions, which are the main loads of this research, could be simulated with TNT equivalent method simply because neither the combustive source nor free distance is determined. The explosion would be originated from a gas leakage in other parts, post-earthquake induced fire or even reckless transportation of combustive materials (Bariha et al., 2016; Bloch and Wurst, 2010; Kong et al., 2018; Pula et al., 2006; Moradi et al., 2021). Given the situation, consequence analysis is intended to provide credible data. With this in mind, an offshore site was subjected to vigorous studies, releasing useful information. As a result, it was concluded that a flash fire would affect a 60-meter-diameter circle. Meanwhile, at the very same location a BLEVE influences 20-meter-diameter circle (Pula et al., 2006).

There are no ubiquitously valid blast load parameters although two common scenarios are widely used in models that can be summarized as below:

- High pressure and short duration;
- Low pressure and long duration (Hansen et al., 2010; Pula et al., 2006).

Chen and Wang (2012) highlighted the shock wave absorption via EPS sandwich panels to safeguard the main structures, especially in offshore sites.

The attentions were drawn to DAF with regard to the pipes weight distribution in by Nelson et al. (2015). In this research, DAF equal to 1.5, proposed as the highest number in Biggs SDOF graphs, was acknowledged as a non-conservative coefficient for racks (Aarønaes et al., 2015). There are practical limitations when it comes to applying explosion on structures. Firstly, loads are not fully known, so that they are estimated unless the explosives are determined in both quality and quantity. Secondly, the operation is assigned as a linear correlation between time and pressure. Thirdly, dynamic interactions are usually neglected due to the complexity of details (Aarønaes et al., 2015; Su, 2012)

2. Material and Method

2.1. Material

2.1.1. Geometry and Physical Features of Racks

The modeled structure now is in operation at Khorasan-Iran petrochemical Complex and is to transport raw material between a few parts by steel pipes. The geometric features of the rack are summarized in Table 1. This rack was selected due to the complexity and diversity of sections which makes the results closer to the actual behavior of similar racks. Also, it would be a full-scale analysis compared to previous research in which simplifications have taken into account as sections were assimilated to a single section due to the complexity of analysis and also blast pressure was imposed on joints instead of the frames.

Table 1. Physical parameters

Feature	Definition
Length	102.85 m
Height	12.6 m
Span length	10 m
Lateral resistance system	Braced frames
Longitudinal resistance system	Ordinary frames
Intersection with other Racks	No

According to collected information, either from field inspection and as-built maps, the sections utilized in the construction are demonstrated in Table 2 as well as pipes' sections in Table 3. Also, the interconnected joints have been made from welding and bolts, which are reported highly fine. As like as most of Iran's infrastructures, the main design is dependent on the functionality of the rack under seismic loads, for which an importance factor equal to 1.25 was assigned (vital vessels).

2.1.2. Materials

The nominal yield stress of the steel is approximated 240 Mpa with ultimate stress of 370 Mpa and module of elasticity is estimated 203 Gpa. However, ASCE (2006) proposes, the nominal stress should be modified with coefficients because material gains additional strength in the face of dynamic loads. According to ASCE (2006), the more rapid a deformation shapes, the yield stress intensifies more. This increase is projected about 10% to 30%, dependent on the deformation rate (ASCE, 2006).

2.2. Method

2.2.1. Analysis Approach

Generally, MDOF analysis (Eq. (1)) is employed in the case of frames under blasts since the coincidence of axial forces and bending moments are calculated. MDOF can be utilized with 2D and 3D approaches.

Table 2. Elements sections

Beams type	Columns type	Braces type
W6 × 15	W6 × 20	L3 × 3 × 1/4
W8 × 21	W8 × 31	L4 × 4 × 1/4
W8 × 24	W10 × 45	2 L3-1/2 × 3-1/2 × 1/4
W8 × 35	W12 × 53	2 L4 × 3 × 1/ 4
W10 × 35	W12 × 87	2 L4 × 4 × 3/ 8
W12 × 79	W12 × 792	L4 × 4 × 1/4
W12 × 96	W14 × 78	2 L5 × 5 × 3/8
W14 × 74	W16 × 100	—-
W16 × 89	—-	—-
W16 × 100	—-	—-

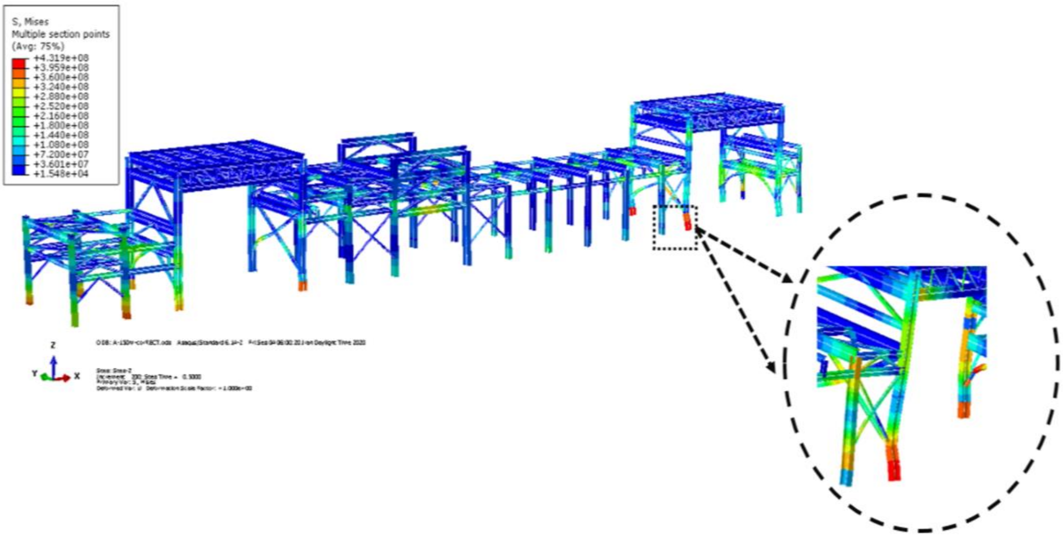


Fig. 1. The configuration of pipe rack and critical base sample

Table 3. Average of WOP/WP for critical nodes

Pipe diameter (inch)	Weight of contents (kg/m^2)	Weight of pipes (kg/m^2)
2	0.2	0.45
4	0.8	1.42
10	4.97	5.6
4	0.8	1.42
2	0.2	0.45
10	4.97	5.6
10	4.97	5.6
2	0.2	0.45
3	0.45	1.08
3	0.45	1.08
8	3.18	5.44
12	7.16	10.47
8	3.18	6.44
3	0.45	1.08

$$M\ddot{u}(t)+C\dot{u}(t)+F_{\text{int}}(t)=F_{ext}(t) \qquad (1)$$

where M: is mass, C: is damping, F_{int}: is internal force, F_{ext} : is external force, $\ddot{u}$: is acceleration, $\dot{u}$: is velocity and T: is time.

The geometric and mass symmetry dictate the necessity of 3D modeling in pipe racks; however, a complete symmetry seldom can be observed as height and plan irregularities govern (Aarønaes et al., 2015; ASCE, 2006; Su, 2012). Previous researchers have underlined the shape of pipe support but these supports were eliminated on the simulation (Aarønaes et al., 2015; Su, 2012). Observing details and surveying the geometry of the rack show that pipes go down and up despite previous studies in which pipes were assumed straight. These movements, which are about to be investigated closely, can constrain frames together. For structural elements b31 type was selected because not only large axial strains as well as large rotations is formulated but also transverse shear strain is included. This eventually leads to distortion of the cross-section which is taken into calculation (Dassault Systèmes, 2015).

ABAQUS 6.14 (Simulia, 2015) was used for non-linear dynamic and static Finite Element analysis. Afterward, a python code with contribution of NUMPY, Pandas and Matplotlib libraries was developed to facilitate data extraction and pertinent graphs among a plethora of unprocessed information.

2.2.2. Blast Properties

When a blast wave propagates toward an object, three presumable hit-reflects may happen. If the stroked object (frames) has smaller dimension in one direction, the only effective load is dynamic pressure, as Figure 2 portraits (Aarønaes et al., 2015; Su, 2012).

There are copious notes on determining blast parameters and proposing closed-form equations for the calculation of pressure wave behavior. At first, Brode (1995) formed Eq. (2) as below.

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3}, 0.1bar < P_{so} < 10bar$$
$$P_{so} = \frac{6.7}{Z}, 0.1bar < P_{so} < 10bar \tag{2}$$

where P_{so}: is peak side-on overpressure and Z: is distance from blast source.

Having brode documents, Newmark and Hansen (1961) devised another time-honored formula (Eq. (3)) in which W and R are explosive weight and object-to-source distance, respectively.

$$P_{so} = 6784\frac{W}{R^3} + (63\frac{W}{R^3})^{0.5} \tag{3}$$

Eventually, Henrych (1979) formulated pressure (Eq. (4)) magnitude based on Z as the scaled distance.

$$P_{so} = \frac{14.072}{Z} + \frac{5.54}{Z^2} + \frac{0.357}{Z^3} + \frac{0.00625}{Z^4}, 0.05bar < Z < 0.1$$
$$P_{so} = \frac{6.194}{Z} + \frac{0.326}{Z^2} + \frac{2.132}{Z^3}, 0.1bar < Z < 0.3$$
$$P_{so} = \frac{6.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3}, 0.3bar < Z < 10 \tag{4}$$

The imposed dynamic pressure is classified into three major types that cover the suggested values of ASCE. There are a handful of formulas which are mostly based on experimental tests, but Table 4 is derived from UFC dimensionless graphs (Unified Facilities Criteria (UFC (3-340-02), 2008). Also, blast duration including 35 ms, 50 ms, 75 ms and 90 ms are extracted from UFC graphs.

Table 4. Selected blast magnitude

Blast type	Scaled distance	P (kPa)	Dynamic pressure (kPa)
A	7	137.9	55.2
B	8	103.4	27.56
C	10	68.95	13.8

3. Discussion and Results

3.1. Nonstructural Components

In this research, all of the columns were subjected to rigorous investigation since the abundance of beams provides the structure with high number of load transition paths. These columns, based on their elevations, were assorted to long and short elements. Short columns are in the range of 7 m to 9 m and long ones go in 10 m to 12 m length category. In all columns, the pipe layout exists at the apex. Long columns have been shaped to conduit pipes through a direction to not intersect with other equipment due to the rack location and restrictive access space. Because of divers sections and different levels, unlike available research, mesh sensitivity analysis ought to be conducted all over again and existing results are no longer viable. The results according to Figure 3 indicate the convergence with 3700 total elements with 0.8 cm mesh size.

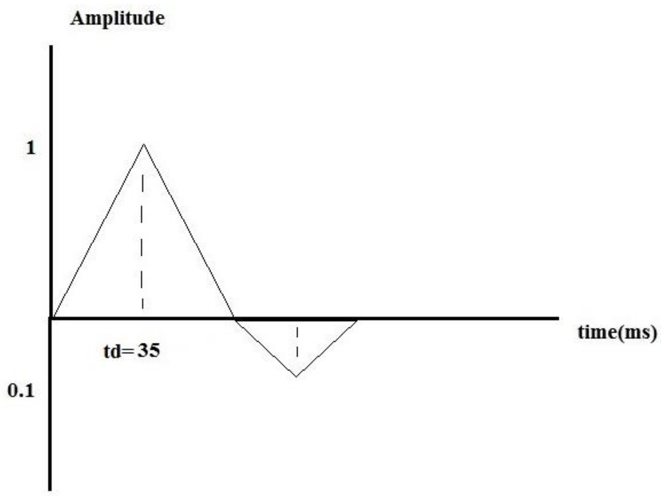


Fig. 2. Average pressure-time variation (UFC (3-340-02), 2008)

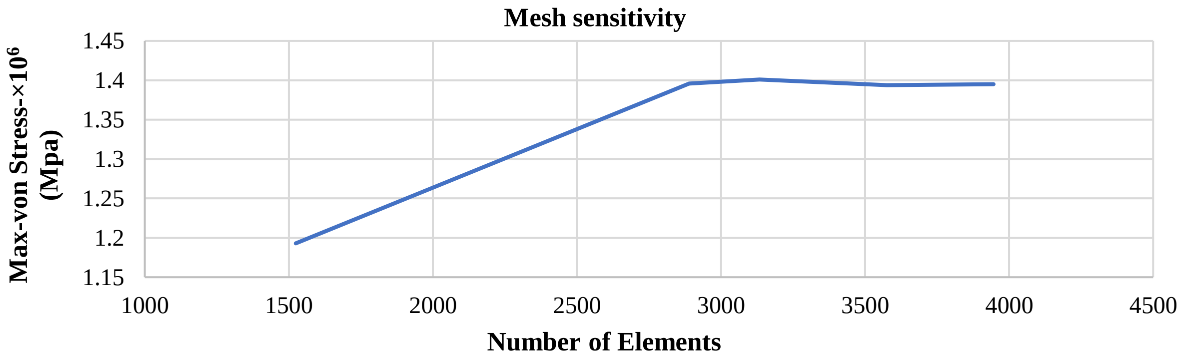


Fig. 3. Mesh sensitivity analysis

This finding will address a controversy in racks carrying pipes. Although important in material consumption, the pipe will not be playing a key role in the magnitude of stress at the critical elements in types A and B. Figure 3 clarifies the slight difference in one of the critical bases (Figure 1).

To pour into details, two sets of analysis, including WP (shorthand for with pipe) and WOP (shorthand for without pipe) were undertaken. The results in Table 5 imply that owners can ignore the pipes in models while remaining conservative. This table discloses the average of WOP/WP of critical nodes located at the bases.

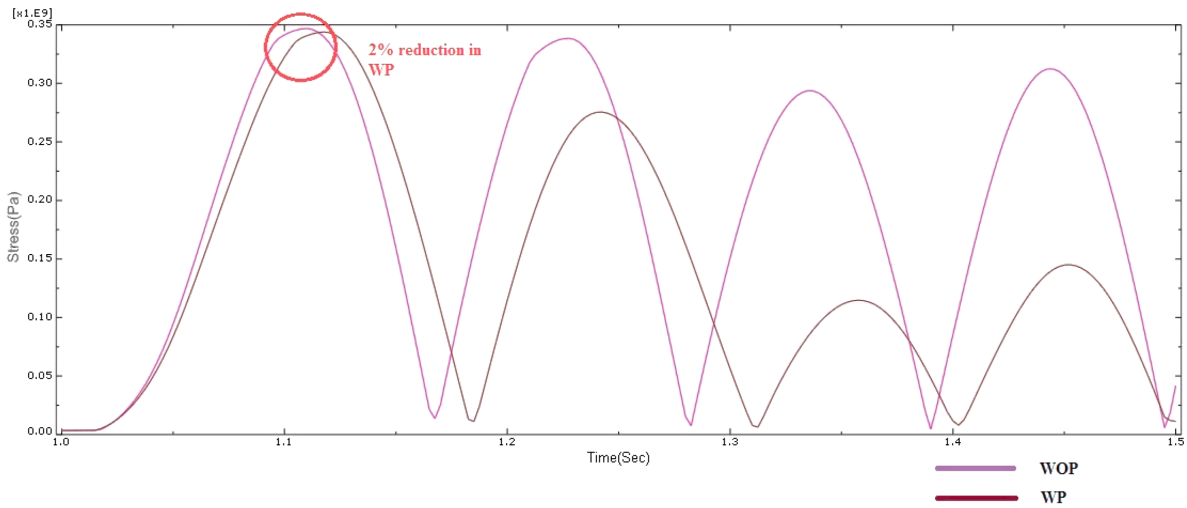


Fig. 3. Slight difference critical bases

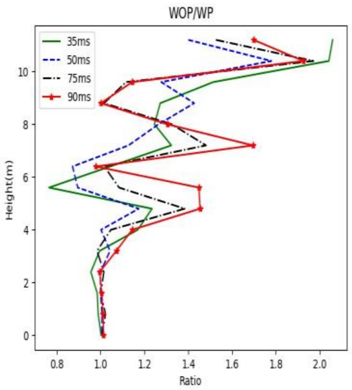
Table 5. Average of WOP/WP for critical nodes

Type of explosion	Duration	Average (WOP/WP)
A	35	1.33
	50	1.2
	75	1.11
	90	1.06
B	35	1.02
	50	1
	75	1.03
	90	1.03
C	35	1.06
	50	1.02
	75	1.04
	90	1.02

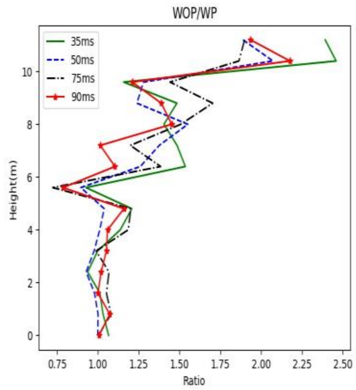
Nonetheless, if the aim is an optimized design, one should have pipe racks modeled with pipes. Figures 4a-4f show the change of WOP/WP ratio in height and its dependence on the duration. This ratio, generally, rises when the elevation increases. In the following critical columns, WOP/WP for all types of blasts, at the bases, places around one. But as the height grows, the coefficient surges in two sharp steps. The first one is at the height of 6 m where the first floor, attached to the column, emerges. The second one happens at the top to which pipes are connected. For example, WOP/WP for column-1 experiences 100% increase followed by 50% growth. This pattern could be applied to other columns too.

In the case of explosion Type A, there is a plateau for WOP/WP around one, which is the direct consequence of transition into plasticity threshold as Figure 5a-5f depict, followed by changes.

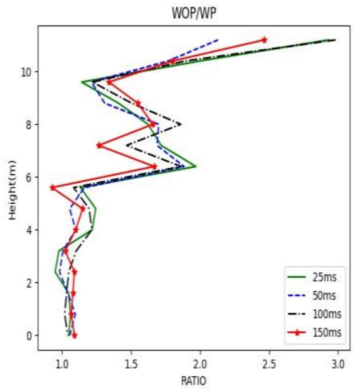
Seemingly for all nodes which are not necessarily critical nodes, the interquartile range of columns' WOP/WP stands more than one with considerable positive skew; simultaneously, nodes below one are rare and located in non-critical areas.



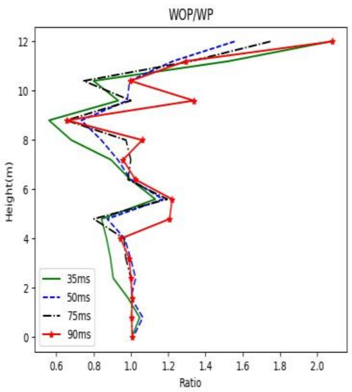
(a) **Critical Column-1 Type A Blast**



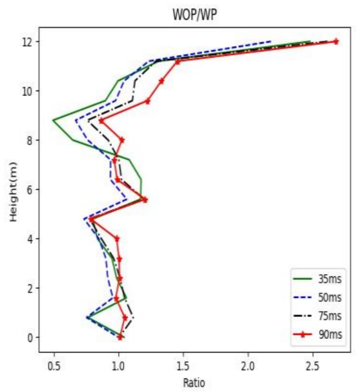
(b) **Critical Column-1 Type B Blast**



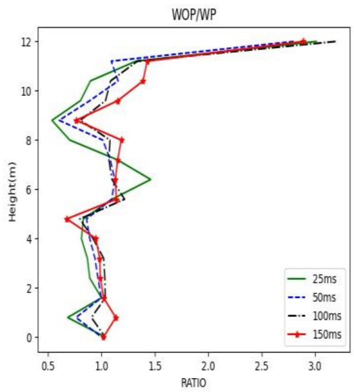
(c) **Critical Column-1 Type CBlast**



(d) **Critical Column-2 Type A Blast**

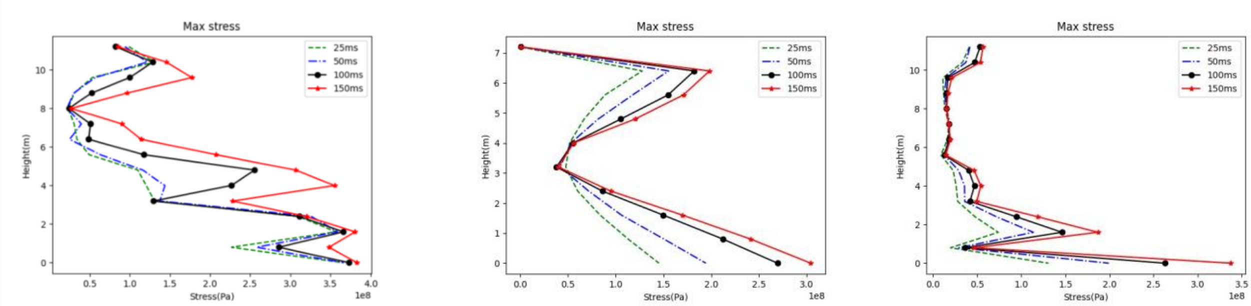


(e) **Critical Column-2 Type B Blast**

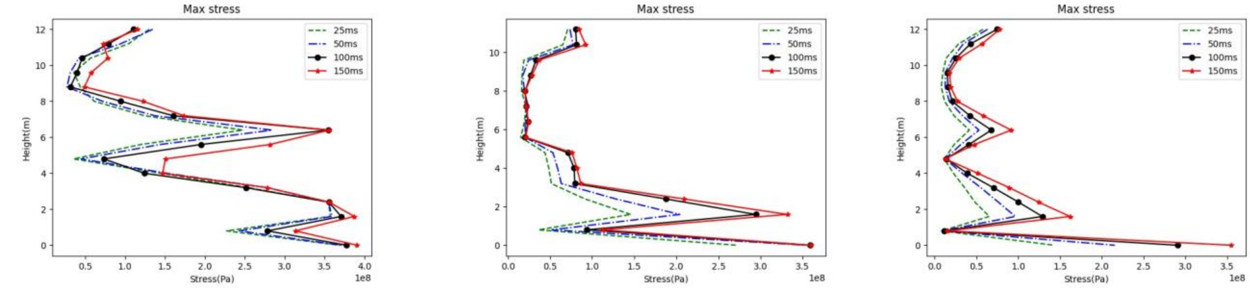


(f) **Critical Column-2 Type CBlast**

Fig. 4. WOP/WP for two critical columns

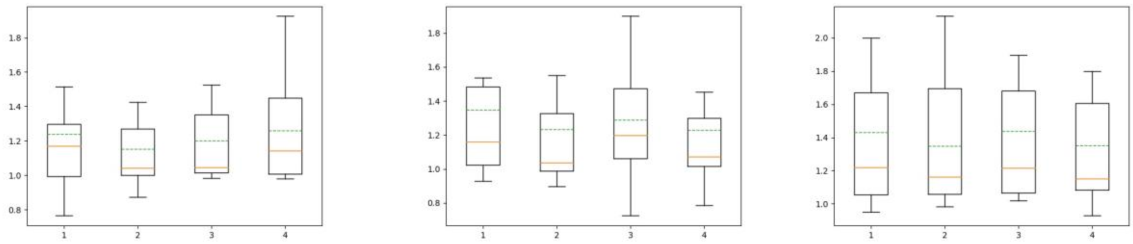


(a) **Critical Column-1** (b) **Critical Column-1** (c) **Critical Column-1**



(d) **Critical Column-2** (e) **Critical Column-2** (f) **Critical Column-2**

Fig. 5. Stress distribution for two columns



(a) **WOP/WP Box Chart Critical** (b) **WOP/WP Box Chart Critical** (c) **WOP/WP Box Chart Critical**

Fig. 6. Box chart

Furthermore, looking at displacements would be more practical and convenient than stress contours to base the primary judgment on since pipes in pipe racks bring intrinsic limitations on maximum tolerable deformation, becoming stricter where joints or flanges had been placed. Nevertheless, calculations (Table 6) reveal no meaningful difference between deformation on drift-controlled spots in WOP and WP conditions. This may stem from the rapid transience of propagated waves which pipes rarely find the chance to dissipate the initial momentum. So this slight contradiction could be overlooked. As this table depicts, this is predictable that both the duration and intensity of blasts have direct effect on the maximum deformation. The minimum lateral deformation in WOP caused by C-35 ms explosion is 1.7 cm, whereas the maximum appears to be 13.6 cm by A-90 ms. Meanwhile, the reduction percentage fluctuates between 9% and 14 % for B-50 ms and A-90 ms, respectively.

3.2. Static and Dynamic Approach

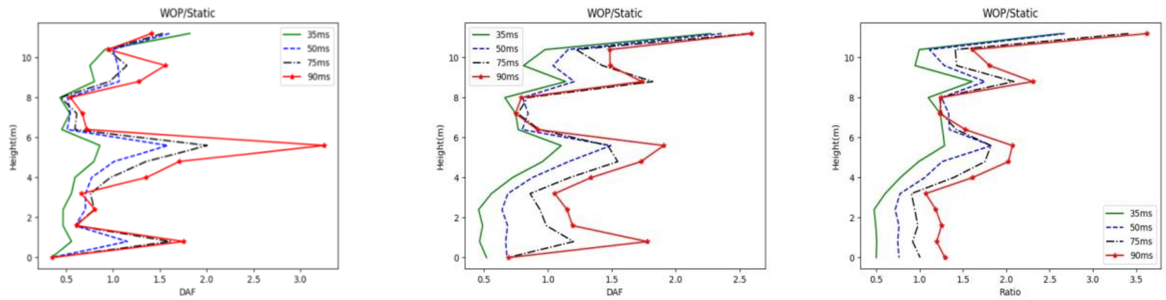
It is worth mentioning that the analysis method would put a burden on owners either financially or technically. In other words, providing the design team with fast-calculating computers and deft operators for interpretation would be unseen angles of an optimized design. So that a static analysis would be much more of predilection than non-linear dynamic (NL-dynamic). This is simply because of the convenience and rapidity of this method. To peruse the validation of static manner, an index in Eq. (5) was defined.

$$DAF = \frac{Stress_{NL-dynamic}}{Stress_{static}} \quad (5)$$

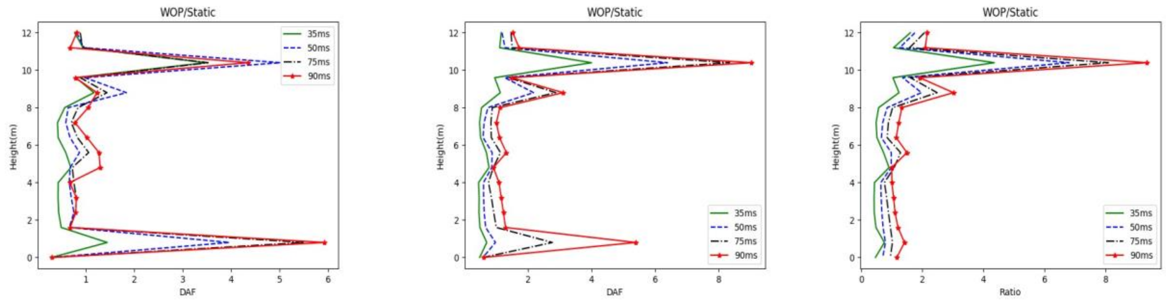
The index's values corroborate the credibility of static analysis in short durations (35 ms and 50 ms) for both types B and C in over 90% for critical elements. However, up until the stress is below the yield state, DAF rises where duration and intensity boost. Noteworthy to say, dynamic analysis remarkably differs from the static approach where stiffness irregularity occurs. Therefore, static analysis qualification defeats and the non-linear dynamic approach is strongly suggested if stiffness irregularity exists. DAF in columns' heights is depicted in Figures 7a-7f. As the height increases from the base, overall DAF grows. Meanwhile, this growth becomes significant in stiffness irregularities. This similar pattern in critical columns is constituted from three phases. Just one meter above the bases, strengthened by braces, the first irregularity boosts DAF by more than 50%. Then at the first-floor intersection, the second phase of escalation could be observed. Finally, at the tops, DAF, multiplies. The maximum DAF is approximately 6, which indicates the static analysis may underestimate the exact values by 600%.

Table 6. Reduction percent of WP to WOP

Type of explosion	WOP deformation (cm)	WP deformation (cm)	Reduction (%)
A-35 ms	4.67	4.18	10.4
B-35 ms	2.41	2.02	16.3
C-35 ms	1.17	1.03	11
A-50 ms	7.9	6.28	11.4
B-50 ms	3.3	3	9.03
C-50 ms	1.77	1.53	13.5
A-75 ms	9.46	8.31	12.1
B-75 ms	4.48	3.91	12.8
C-75 ms	2.2	1.9	12.6
A-90 ms	13.6	11.8	13.7
B-90 ms	5.7	5.05	11.4
C-90 ms	2.8	2.4	11.2



(a) Column-1 DAF in Height, Type A (b) Column-1 DAF in Height, Type B (c) Column-1 DAF in Height, Type C



(d) Column-2 DAF in Height, Type A (e) Column-2 DAF in Height, Type B (f) Column-2 DAF in Height, Type C

Fig. 7. DAF coefficient for two columns

3.3. Safe Distance

Arrangement of equipment, particularly those that may conduct or store combustive materials, should be checked as having a safe distance to pipe racks decreases the risk of severe damages. a list of scenarios and safe distances could be helpful to corresponding engineers or technicians locating other parts. If the safe distance verification is ignored, a tanker explosion may interrupt the daily activities of the whole process area as well as burdening the rehabilitation costs. Given how much safe distance is required, designers could acquire what location would be appropriate for putting other facilities such as gas reservoirs and tank. If the amplitude of potential blast is in the range of Type A, the corresponding immune distance for the pipe rack is determined between 50 m and 19.7 m according to Table7. This table might be more important in the case of designing main pipe racks or those that carry highly explosive and flammable materials. In regular racks, developing this table is optional but helpful in having a vivid overview of what is a well-arranged plan. The velocity (ft/sec) of wave is calculated with Eq. (6). In this equation P_{s0} should be in psi unit. The velocity and duration will determine the safe distance.

$$U = 1130(1 + 0.058P_{so})^{0.5} \qquad (6)$$

4. Conclusions

In this paper, 3D Finite Element models were developed first, with ABAQUS software to simulate the behavior of a pipe rack under blast pressure. The models cover both non-linear material characteristics and non-linear geometrical parameters. According to the results main findings are listed as below:

- Non-structural components (pipes) have not meaningful effect on stress results at critical nodes and these pipes could be ignored in design process; however, if the aim is developing an optimized model, the pipes should be taken into design.
- The numerical outputs show that static analysis leads to conservative results only when the duration is less than 50 ms. In contrast, static analysis is not useful as considerable errors (even more than 100%) arise in long-duration blast waves. Thus non-linear dynamic analysis is necessary and more reliable. Also, DAF coefficient is significantly dependent on irregularities. So that non-linear dynamic analysis results in more accurate calculations and is suggested if irregularities exist.
- Finally, the safe distance table would be beneficial for engineers to have a well-organized arrangement of sectors. With this consequence analysis in hand, due to the location of pipe racks and importance of the vessels or highly combustive sectors could be outlined properly in order to mitigate the severity of damages in a confluence of accidents.

Table 7. Safe distance

Type of explosion	Duration (ms)	Dynamic pressure (kPa)	Distance from source (m)
A	35	55.15	19.77
B	35	27.57	18
C	35	13.78	16.5
A	50	55.15	27.6
B	50	27.57	25.75
C	50	13.78	23.6
A	75	55.15	41.5
B	75	27.57	39.7
C	75	13.78	35.5
A	90	55.15	50
B	90	27.57	46
C	90	13.78	42.6

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