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Global Dynamic Response of Piperacks and Steel Modules Subject To Accidental Vapor Cloud Blast Explosions

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ABSTRACT. *Vapor cloud explosions (VCEs) are very common in operating refineries and petrochemical plants. Limited guidelines are available in industry for design steel modules or piperacks subject to blast loading. The paper aims to provide industrial guidelines for practicing engineers and steel fabricators to optimize the design of steel modules and piperacks subject to blast loading. Analytical procedure is presented to calculate global dynamic response of piperacks and steel modules using multiple degree of freedom (MDOF) dynamic model. Operation loadings and structural design criteria of piperacks are also described. The formation mechanism of Vapour Cloud Explosions (VCEs) is then briefly described. Numerical example is then provided to illustrate the computation procedure. The proposed procedure avoids excessive computational cost required by numerical (FE) (CFD) procedures and can be used in practice to evaluate dynamic response of piperacks subject to blast loading with reasonable accuracy.*

Keywords; Piperacks, steel modules, vapor cloud explosions (VCEs), refineries, blast analysis.

1. INTRODUCTION

Piperacks are used extensively in petrochemical plants and refineries to support pipes, power cables and instrument cable trays that are running between various process units. Occasionally, they are used to support mechanical equipment, vessels and access platforms. Piperacks are also used in some projects to transport steam to remote oil wells and deliver recovered bitumen to the upgrader. Piperacks are essential structures that impact the capital cost of most projects. Consequently, their design basis and fabrications procedure must be clearly described in most project documents.

Fires and explosions in process zones have resulted significant losses in the past. Minimizing losses in hazards areas require proper plant layout and proper engineering design. Explosions in petrochemical plants are classified as vapor cloud explosions (VCEs). Plant design criteria should minimize intense fire and blast effects on critical structures that are located within the process zones during an explosion. Safety rules and spacing requirements shall be carefully implemented by engineers in order to minimize damages.

Piperacks should be designed to withstand blast explosions and reduce human and financial damages or losses. Limited guidelines are available in practice that deals with blast design of piperacks. North American codes AISC [1], ASCE [2], CSA-S16 [3],NBC[4], CSA-S136 [5] and industry standards address mainly buildings structures. Design specifications for non-building structures are often developed by the private companies. Although the framing system seems simple, loading pattern may not be clear. Consequently, extensive efforts are required by the engineers to assemble design information.. Furthermore, little emphasis is given to simulate vapor cloud loadings on piperacks.

Much of the research work in published literature focused on blast response of residential buildings. Kumar, et al, [6] presented experimental and numerical investigations for reinforced concrete slabs subject to blast loading. Lin, et al [7] presented a procedure for progressive collapse analysis of steel frames subject to blast load. The explosion source is assumed to initiate inside the building. Li and Aoude [8] studied influence of reinforcement layout on blast performance of beams with high-strength concrete and high-strength steel reinforcement. Foglar and Kovar [9] presented test results for precast concrete slabs with variable fiber strength subject to blast explosions using 25 kg of TNT charges. Buchan and Chen [10] investigated blast resistance of FRP composites and polymer strengthened concrete. Fu [11] performed numerical dynamic analyses for 20-storey frame using FE Software ABAQUS [12]. Tsai and Lin [13] investigated progressive collapse resistance of buildings. Harrison [14] discussed blast performance of blast resistant buildings. Kim and Kim [15] studied progressive collapse of moment resisting steel frames. Qiao, and Zhang [16] quantified the potential overpressures due to blast loading and the potential gas build up by using Computation Fluid Dynamics (CFD) for onshore or offshore facilities.

Seible, et. al. [17] compared similarities and differences between blast and seismic hazards for bridges using blast field tests and numerical procedures. Silva and Lu [18] studied the effect of composite materials on blast resistance capacity of one-way reinforced concrete slabs. Wu et al [19] conducted series of tests to investigate blast resistances of slabs using various composite reinforcements. Nam, et al [20] presented experimental models to study structural behavior of reinforced concrete slab retrofitted with glass fiber reinforced polymer subject to blast pressure. Johns and Clubley [21] performed dynamic simulations using computational fluid dynamics (CFD) procedure to study blast wave interaction applied to masonry structures. Numerical analysis and tests using full scale models were used to compute the dynamic response. Jayasooriya, et al [22] investigated the impact of near field explosions on reinforced concrete frames using (FE) software SAP 2000 [23] and LS DYNA [24]. Bedair [25-29] addressed critical design aspects of various structures used in heavy industrial projects.

Although most of the research work was fueled by the increased demands to achieve economical and reliable procedures, little attention was given for non-residential structures. Limited engineering guidelines and standards are available in practice for design of piperacks and steel modules subject to blast loadings. Furthermore, current building codes are not adequate for design of these structures and additional provisions are needed to define blast loading parameters and limit the structural response.

The present paper is aiming to fill this gap and present simplified analytical procedure for analysis of piperacks subject to accidental vapor cloud (VC) blast explosions that are encountered in refineries and petrochemical plants. In the first stage, the structural system and operation loadings are briefly described. Global dynamic response of piperacks is then addressed and approximate expressions are proposed.

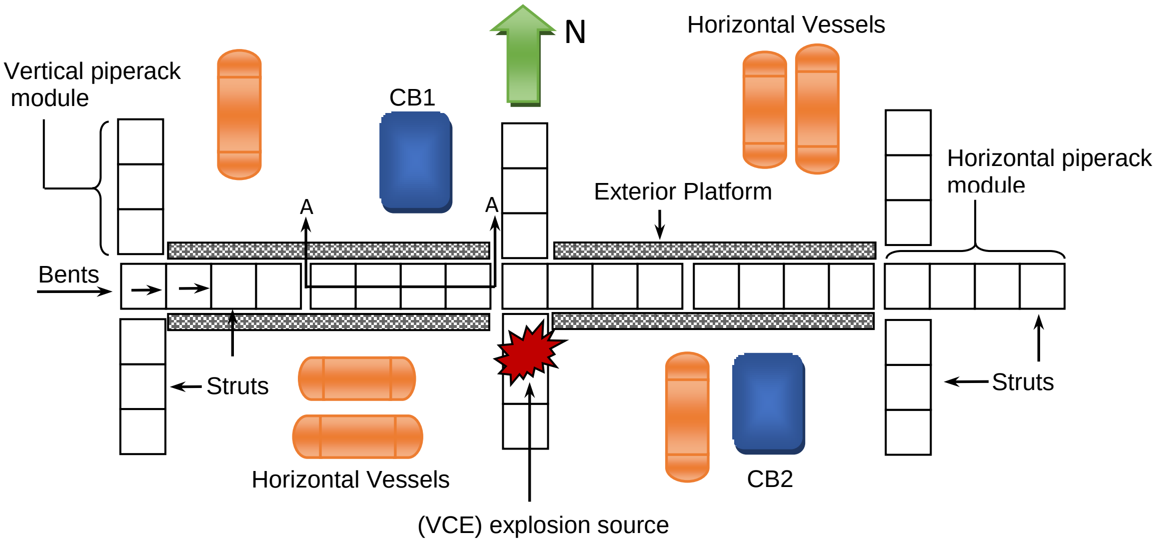
The paper provides useful tools that can be used in industry to calculate the piperack dynamic response with little computation cost compared to numerical finite element (FE) method or computational fluid dynamic (CFD) procedures. The described approach can also be used to optimize the piperack designs and reduce project capital costs.

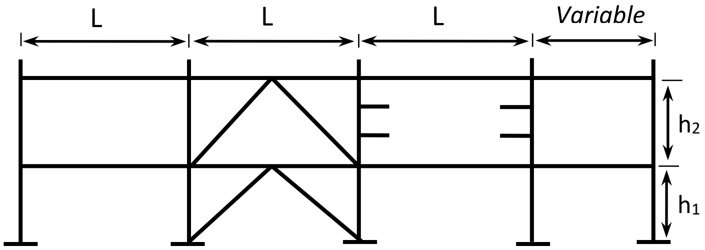
2. PIPERACK STRUCTURAL SYSTEM

Consider a typical piperack layout shown in Fig.(1) in a process zone. The direction of north (N) is shown by the top grey arrow. Horizontal piperack segments consist of four sub-modules as illustrated in section A-A. Each of the vertical piperack segments consists of single modules. Control buildings (CB1) and (CB2) are denoted by blue color. Horizontal vessels are located in the four quadrants and shown by orange color.

Note that piperack size and supporting beam elevations are dictated by piping requirements. Section (A-A) shows piperack elevations running in the (NW) quadrant. The structural framing system consists of multiple transverse bents spaced by distance (L), connected by longitudinal struts. It is practical to use identical module dimensions to simplify the fabrication procedures, (i.e., equal column spacing L). End bays can then be variable.

Diagonal bracings are used in the vertical plane, to resist lateral loads. In some cases knee bracing system is used to widen the access area under the piperack. Horizontal bracings are required for modularized piperacks to resist lateral forces induced during transportation and installation. It is economical to remove horizontal bracings after pip-rack installation to clear space for vertical pipes.





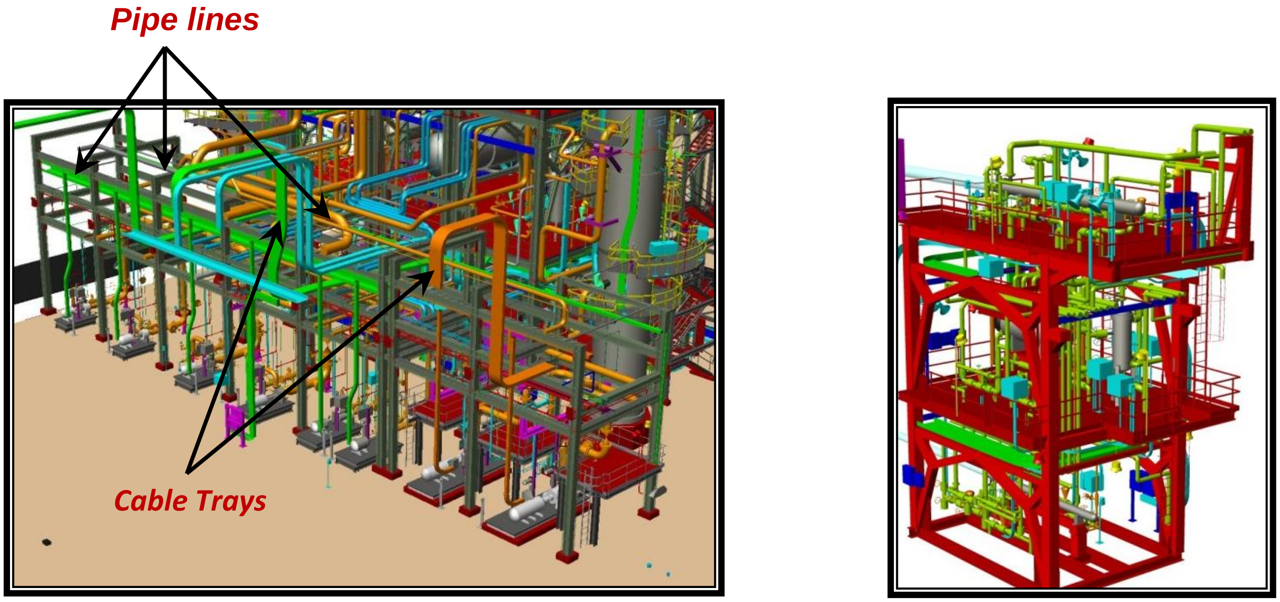
a) Section (A-A)

Fig.1: Piperack Layout out and Elevation

Piperack modules are assembled in the construction site using cranes. It is common to use four lifting points for small piperack modules. The load distribution on each lifting point must be calculated by the engineer and labeled on the structural drawings. Piperacks consist of either single level or multi-levels, depending upon piping design. Maintenance platforms might be provided at each level. Note that the dimensions (h_1) and (h_2) shown in section A-A of Fig.(1) are dictated by piping requirements.

Fig.(2a) shows three dimensional snapshot view of a piperack structure designed in a Gas Recovery Unit (GRU) in oil sand upgrader. The structural steel is assigned the grey color. Also pipe guides and anchors are not shown for clarity.

Figure (2b) shows illustrative example of typical steel module that contains pipes, equipments and electrical cable trays. Steel modules are commonly fabricated off-site and out-fitted with piping, electrical, instrumentation and mechanical equipments. Maintenance ladders are also attached on the side of these modules. To simplify fabrication and construction procedures, bolted connections can be used in all steel design. In some cases, secondary members are connected in the construction site after assembly. Mechanical equipments and electrical junction boxes can be installed on the to the primary floor beams at various elevations using bolted connections, as shown in Fig (2b).



a) PIPERACK MODEL b) STEEL MODULE

Fig.2: Piperack and Steel Modules Structural System

3. DESIGN BASIS

Piperacks are designed for normal operation loads that include dead loads, live loads wind loads, thermal loads, friction, anchor and guide loads. Dead load (DL) consists of equipment, structures, permanent fixtures, fireproofing, insulation, fixed partitions, piping and electrical material.

Live loads (LL) of pipe racks shall include temporary/maintenance loads, such as personnel, miscellaneous tools/equipment, moveable partitions and stored materials. Minimum (LL) for floor plates and grating is 4.8kPa. Wind load (WL) must be applied at the longitudinal and transverse directions of the piperack. Uniform distribution shall be applied to member perpendicular to the wind direction. Wind forces on pipes and cable trays shall be applied as uniform distribution or point load at the mid-span of the supporting beams. Torsion due to the wind load on the handrail is usually negligible.

Snow load (SL) shall be calculated and distributed proportionally for multilevel piperacks. For example, (50%) could be applied to the upper levels and the remaining (50%) to be distributed between lower levels. Minimum (SL) load value is 1.0 kPa. Note that the tributary area of snow load depends upon the number of pipes, cable trays,...etc.

Earthquake load (EL) shall be calculated using relevant codes. Piperacks shall be designed as ‘conventional construction’ unless located in high seismic zones. In locations where seismic design is mandatory, the project geotechnical report shall be utilized to establish the parameters required for foundation design.

Thermal loads (TL) shall be based on the installed temperature and the minimum/or maximum ambient temperatures. Movement joints shall be provided for piperacks exceeding 80 meters long.

Friction forces (FL) are induced by hot pipelines sliding on pipe supports during start-up and shutdown operations. For pipe diameters less than 300 mm, a uniform horizontal friction load distribution can be used.

Impact load factors (IL) shall be used for design of modular piperacks or steel modules in order to account for lifting and transportation conditions

4. VAPOR CLOUD BLAST LOADING

Accidental petrochemical explosions result when flammable materials are mixed with air to form vapor clouds that when ignited can cause blasts. The magnitudes of blast pressure and impulse duration are determined using Baker-Strehlow-Tang and the Netherlands Organization (TNO) Multi-energy procedures. It very difficult to predict the intensity of the vapor cloud blast loads in congested areas. Therefore, conservative assumptions are made in practice to use worst case scenario. Furthermore, in some cases non-essential structural elements are allowed to be damaged as long as collapse is prevented. The common reference used for empirical design is published by U.S Department of Defense [30]. This manual contains collection of data for explosions related to munitions, manufacturing, handling and storage facilities. ASCE [31], CSA S850-12 [32] and Process Industry Practices [33] also provide empirical parameters for general blast loading resulting from bombs, fires and accidental explosions applied to residential and industrial buildings. It must be noted that North American specifications provide high level procedure for damage classification of blast resistant buildings. The author believes that these procedures should be modified to include piperacks and steel modules.

Petrochemical explosions are classified as vapor cloud explosions (VCEs). Majority of accidental piperack explosions are caused by pipeline leaks. To illustrate the blast mechanism, consider a typical piperack subject to the blast loading shown in Fig.(3). Isolated spread footings are used to support the piperack. If the load is significant, pile foundations can be used alternatively. The columns in this case are supported by concrete pedestals. The ground elevation is denoted by (GE) and is measured from the top of concrete pedestal. Anchor bolts are used to connect the base plates to the concrete pedestals The load resulting from the blast source are created by the rapid expansion of the energetic material, thus creating a pressure disturbance or blast wave radiating away from the explosion source, at time intervals {t_1, t_2, t_3 , t_4}. Shock waves are high-pressure blast waves that travel through air at velocity faster than speed of sound and are also characterized by instantaneous increase in pressure followed by a rapid decay. As the blast wave travels away from the source, the pressure amplitude decreases and the duration of the load increases.

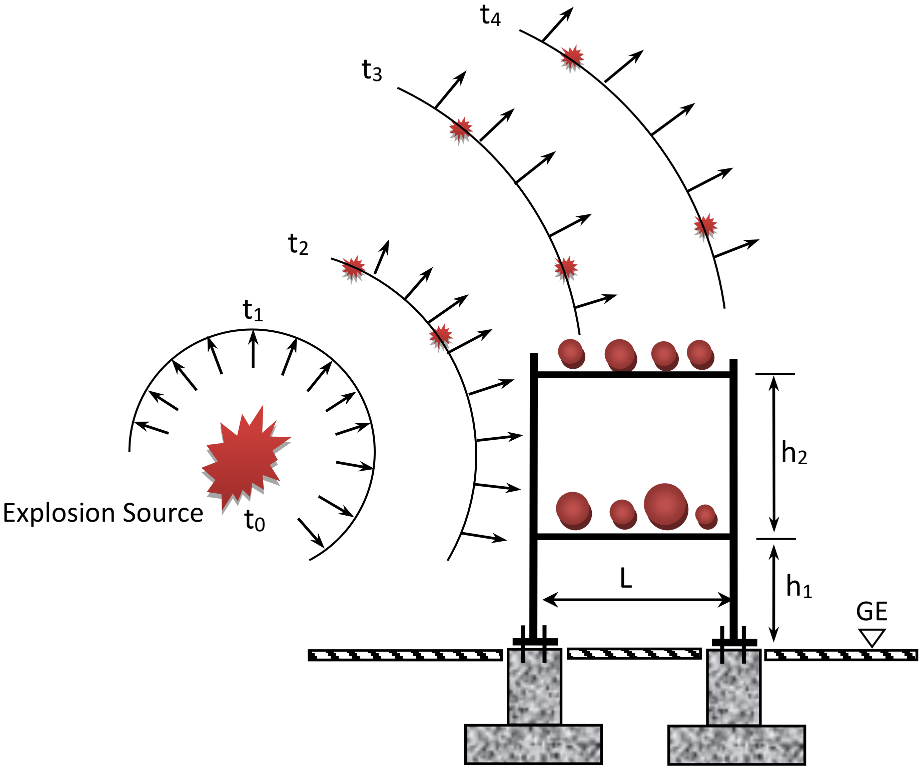


Fig. 3: Typical Vapor Cloud Explosion (VCE) Mechanism

5- PIPERACK GLOBAL RESPONSE

Global dynamic analysis is required to determine the peak dynamic displacements and stresses due to application of the blast load. The mathematical formulation of the idealized dynamic model is summarized in the flow chart shown in Fig.(4). The structural idealization is depicted in blocks (A) & (B).

The piperack notation is shown in block (A). The pipes are represented by the lumped mass (m_1) and are assumed to be uniformly distributed across the width (L). The equivalent floor stiffness at elevation (h_1) is denoted by $(EI_1)_{eqv}$. Similarly, the mass and equivalent stiffness at elevation (h_2) are denoted by (m_2) and $(EI_2)_{eqv}$, respectively. The idealized blast forces are idealized at the joint and denoted by (F_{e1}) and (F_{e2}).

The analysis can be performed using equivalent two degrees of freedom spring-mass oscillator system illustrated in block (B). Note that $\{x_1, x_2\}$ denote the time varying displacement measured from the center of mass and the spring stiffness of each mass are denoted by $\{k_1, k_2\}$, respectively. The governing differential equations for the spring-mass system are shown in block (C). Note that $\ddot{x}_i(t)$ and $\dot{x}_i(t)$ are the acceleration velocity of the idealized mass due to blast loading.

The free vibration equations are shown by the blocks with orange color. The forced vibration blocks are shown by blocks with blue color. The natural frequency of the piperack is determined by setting the right hand side of the equations shown in block (C) to zero. In this case, the system undergoes free vibration.

Equilibrium equations can be expressed using the forms shown in block (D). Note that $[m_i]$, $[k_i]$ and $\{x_i\}$ are given by;

$$[m_i] = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \quad , \quad [k_i] = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \quad , \quad \{x_i\} = \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} \tag{1}$$

If the system is vibrating in normal modes, the two displacements $\{x_1, x_2\}$ are harmonic and in-phase and can be expressed using the following shape functions;

$$\{x_i\} = \{a_i\} \quad \sin(\omega t - \alpha), i = 1,2. \tag{2}$$

where $\{a_i\}$ is a vector that contains the amplitude of motion. Substituting Eq. (2) into equations (D) results into the following normalized characteristic equation:

$$\omega^4 - \delta \ \omega^2 + \beta = 0 \tag{3}$$

Where:

$$\delta = \left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} \right), \quad \beta = \frac{k_1 k_2}{m_1 \ m_2} \tag{4}$$

The natural frequency of the piperack is solution of Eq. (3) and is shown in block (E) of Fig.(4). The corresponding natural periods $\{T_1, T_2\}$ are also shown in block (F).

Determination of the piperack dynamic response due to blast loading requires the solution of coupled differential equations of block (C). These equations can be transformed into a system of uncoupled equations by expressing the solution in form of generalized functions z(t) with normal or orthogonal modes as follow;

$$\begin{Bmatrix} x_1(t) \\ x_2(t) \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{Bmatrix} z_1(t) \\ z_2(t) \end{Bmatrix} \tag{5}$$

Where $\{z_1, z_2\}$ are orthogonal time varying functions that describe vibration mode under blast excitation and $\{a_{ij}\}$ are the associated coefficients that determine the contribution of each mode.

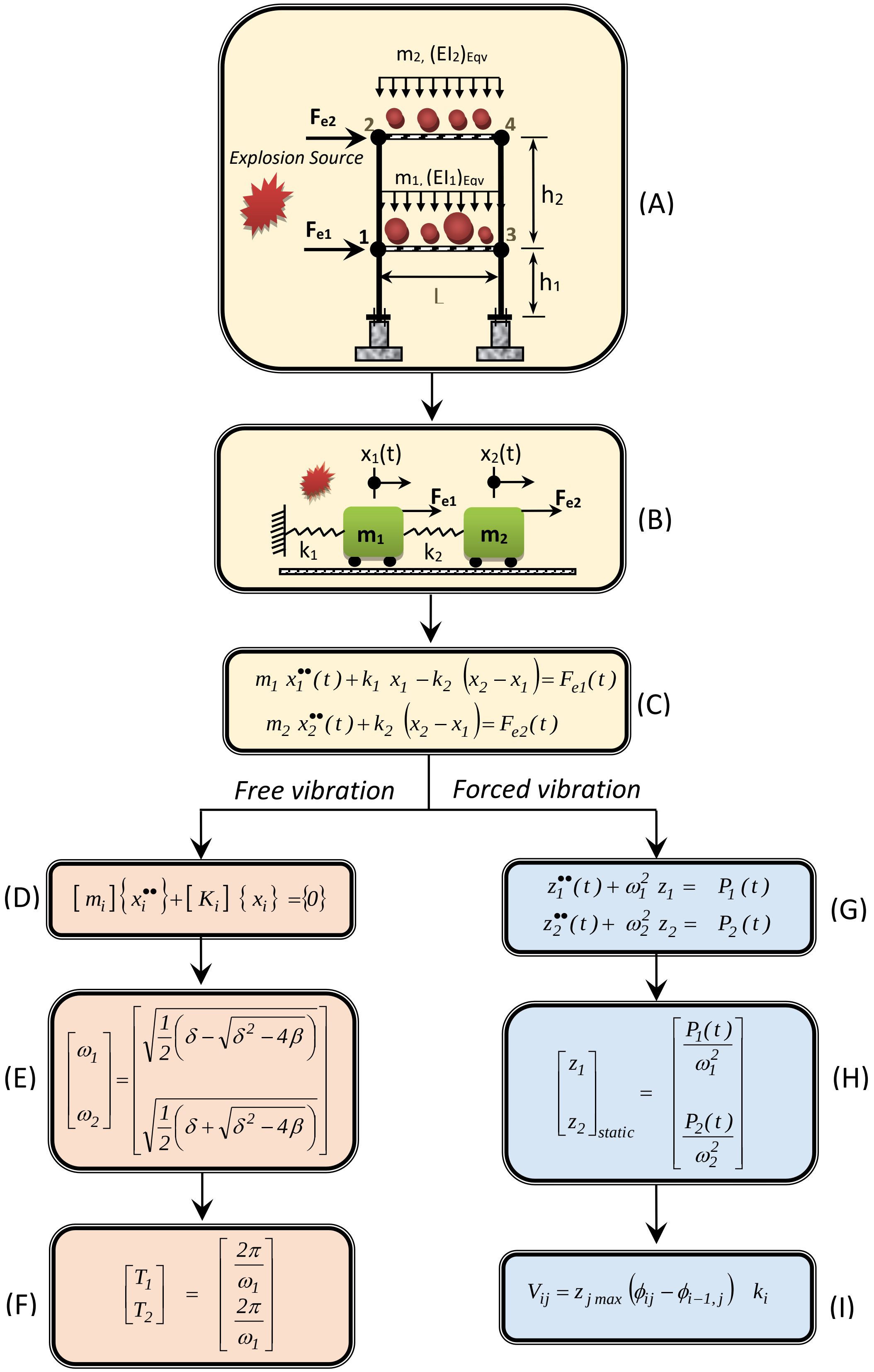


Fig. 4: Mathematical Formulation Summary of Idealized Piperack Model

Substituting Eq. (5) into the equilibrium equations yields the equations shown in block (G). The parameter $\{P_i\}$ is given by;

$$\{P_i\} = \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} \begin{Bmatrix} F_{e1} \\ F_{e2} \end{Bmatrix} \tag{6}$$

where F_{e1} and F_{e2} are the equivalent nodal forces shown in block (A) and (φ_{ij}) is the vector containing the normalized vibration modes and is given by following compacted form:

$$\phi_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{n} m_k \, a_{kj}^2}} \tag{7}$$

Solution of the uncoupled differential equations shown in block (G) can be obtained numerically to determine the displacement profile of the piperack subject to the blast explosion.

An upper limit for the maximum response can be obtained by adding the absolute values of the maximum modal contributions. This can be attained by replacing $\{z_1, z_2\}$ of by $\{z_{1max}, z_{2max}\}$ and adding the absolute values as follows:

$$y_{1\,max} = \left|\phi_{11}\, z_{1max}\right| + \left|\phi_{12}\, z_{2max}\right| \quad , \quad y_{2max} = \left|\phi_{21}\, z_{1\,max}\right| + \left|\phi_{22}\, z_{2max}\right| \tag{8}$$

Eq. (8) provides an upper limit to the maximum response of joints (1) and (2) of block (A). The values of (z_{1max}) and (z_{2max}) can be determined using the following relation:

$$z_{1max} = (z_{1-Static}) * \; DLF_1 \; , \qquad z_{2max} = (z_{2-Static}) * DLF_2 \tag{9}$$

where (DLF_1) and (DLF_2) are dynamic load factor. The displacements $\{z_{1\text{-static}}, z_{2\text{-static}}\}$ are determined using the relations shown in block (H).

The column shear forces can be determined using equations of block (I) that can be expanded as follow;

$$V_{11} = z_{1\max}\,(\phi_{11})\,k_1 \quad , \quad V_{12} = z_{1\max}\,(\phi_{12})\,k_1 \tag{10}$$

$$V_{21} = z_{2\max}\,(\phi_{121} - \phi_{11})\,k_2 \quad , \quad V_{22} = z_{2\max}\,(\phi_{22} - \phi_{12})\,k_2 \tag{11}$$

The maximum shear forces can be obtained using the following relations:

$$V_{1\ \max} = \sqrt{V_{11}^2 + V_{12}^2} \tag{12}$$

$$V_{2\ max} = \sqrt{V_{21}^2 + V_{22}^2} \tag{13}$$

6. NUMERICAL EXAMPLE

Consider the building frame shown in Fig. (3), with (h_1)=(h_2) =12 ft and L=20ft. Column size is W14x61. The equivalent floor stiffness $(EI_1)_{eqv}$=$(EI_2)_{eqv}$ 19.2x10^9 Ib-in^2 and total vertical load on the first level is approximated by (m_1) =4.25 k/ft and on the second level by (m_2) = 5.25 k/ft. By using equations of section (5), the dynamic parameters of the piperack are as follow;

- Natural frequency parameters are given by;

δ = 1837.3, (β) = 398,397, (ω_1)=15.85 rad/s, (ω_2) = 39.83 rad/s

- Natural periods of the piperack are given by;
  (T_1) = 0.4 sec, (T_2) = 0.16 sec.

- Dynamic load factors are given by;
  $(DLF_1)_{max}$=0.57, $(DLF_1)_{max}$=1.22.

- Maximum sway deflection at joint (2) is given by
  $(z_2)_{max}$ = 0.2 in

- Maximum base shear forces are given by;
  $(V_1)_{max}$ =9.0 Kip , $(V_2)_{max}$ = 5.22 Kip.

Therefore, the piperack response can be calculated manually using closed form formulas that avoid numerical (FE) or computational fluid dynamic (CFD) methods. These useful tools can also be used in industry to develop the material take off for piperacks estimate project cost with reasonable accuracy

7. CONCLUSIONS

- Little guidelines available in practice for design of piperacks or steel modules subject to vapor cloud blast loadings. Furthermore, damage classification and assessment procedures for modular piperacks are overlooked by the industry.

- The paper presented analytical procedure to approximate the dynamic response of piperacks and modules. Overview of operational loadings and structural design criteria for piperacks were briefly discussed. The formation mechanism of vapor cloud explosions (VCEs) was then discussed. The expressions required to compute displacements and base shear were then presented. Numerical example was provided to illustrate the computation procedure.

- The paper provides useful tools that can be used in industry to calculate piperack response subject to blast loadings with little computation effort compared to numerical (FE) or (CFD) models. The structural response can be calculated manually using closed form formulas of (5).

- Effective blast resistant piperack structural system should be capable to absorb and dissipate the blast explosion energy while maintaining the structural integrity. The structure must have adequate ductility and strength to resist lateral loads resulting from the blast VCE wave. Current building codes are not adequate for design of modular piperacks. Additional design provisions are required to define vapour cloud blast loading parameters and stipulate limitations on piperack dynamic response.

- Design of piperack member sizes should be based upon the magnitude of blast pressure and impulse duration. The overpressure magnitude in most petrochemical plants ranges between 1 psi and 8 psi. Therefore, it is economical to standardize the piperack size and member cross sections based on the blast load intensity.

- Piperacks should be designed for normal operation and blast loadings. Minimum (LL) in maintenance areas shall be 4.8kPa. Wind load (WL) should be applied in orthogonal directions. Minimum (SL)=1.0 kPa and distributed to all levels. Thermal and friction forces for pipe diameters less than 300 mm shall be uniformly applied to all supporting beams.

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- NOTATIONS

a_{ij}= modal coefficients;
DLF= Dynamic load factor;
$(EI_i)_{eqv}$ = Equivalent stiffness;
F_{e1}, F_{e2} = Idealized nodal forces;
k_i = spring stiffness;
L = width of the pipe rack;
h= height of the piperack
m_i = mass
t = time duration;
t_d = blast duration time;
T_i = Natural Period
VCE = Vapor Cloud explosion;
$(Vi)_{max}$ = maximum base shear
x_i = time varying displacement;
$x_i^{\bullet}(t)$ = velocity ;
$x_i^{\bullet\bullet}(t)$ = acceleration
$Z_{i\text{-static}}$ = displacements
ω_i= natural frequency
δ, β = natural frequency parameters
z_i = orthogonal time varying functions
φ_{ij}, = normalized vibration modes