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Prediction of BLEVE loading on structures

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ABSTRACT

In a previous study by the authors, rigid structure assumption, as commonly used in analysing blast wave interaction with structures, was adapted in investigating the Boiling Liquid Expanding Vapour Explosion (BLEVE) pressure wave interaction with structures to predict BLEVE loads on structures. However, real structures are not rigid and the duration of BLEVE wave is much longer than that from high explosives and may be in the order of structural natural vibration period. Neglecting structural deformation, therefore, may lead to inaccurate predictions of BLEVE loads acting on the structure because structural deformation during the action of BLEVE wave would change the wave and the structure interaction. In this study, intensive numerical simulations are carried out using a validated computer model to investigate the influences of structural stiffness and BLEVE wave duration on the reflected BLEVE pressure on the structure. Based on the numerical results, prediction charts are proposed as a function of the BLEVE wave duration and structural fundamental vibration period for reliable predictions of BLEVE loads on structures. The findings of this study can be used to predict explosion loads in structural design against BLEVE.

Abbreviations

ANN: Artificial Neural Network
BLEVE: Boiling Liquid Expanding Vapour Explosion
CFD: Computational Fluid Dynamics
FLACS: FLame ACceleration Simulator
FSI: Fluid-Structure Interaction
GNN: Graph Neural Network
SLT: Superheat Limit Temperature
UDF: User Defined Function
VCE: Vapour Cloud Explosion

1. Introduction

To mitigate the hazards associated with explosion incidents, it is important to have a proper protective design for structures. Reliable and accurate blast load prediction is crucial for designing structures effectively and economically. For instance, the Unified Facilities Criteria UFC-3-340-02 (UFC, 2008) serves as a widely used design guideline, providing empirical formulae and charts for predicting high explosive (HE) loads, which can be straightforwardly applied by engineers when designing structures.

Accidental gas explosions have been occurring around the world occasionally and causing significant loss of lives and economy. Vapour Cloud Explosion (VCE) and Boiling Liquid Expanding Vapour Explosion (BLEVE), as two main types of gas explosions, received extensive attention. VCE has been widely investigated in recent decades (Atkinson et al., 2017; Oran et al., 2020; Raman and Grillo, 2005; Roosendans and Hoorelbeke, 2020; Sharma, 2020), while BLEVE-related research is still limited. Most BLEVE studies are focused on BLEVE occurring in open space to predict overpressure rather than obtaining the blast loads on structures (Wang et al., 2022b). In fact, BLEVE usually occurs during processing, transportation and storage, which can damage structures, such as buildings, bridges, tunnels, highways, etc. (Bariha et al., 2017). When BLEVE occurs, the blast waves propagate to a structure, and the structure may deform and alter the blast wave flow properties (i.e., reflected waves). This is a multi-physics phenomenon known as fluid-structure interaction (FSI) (Raja, 2012; Chun et al., 2005). Due to the FSI, predicting BLEVE loads on a structure is more complex than in open space.

BLEVE occurs when the pressurized tank suddenly ruptures and the inside liquid is above its boiling point. Two BLEVE types can be

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classified based on the failure temperature, i.e., non-superheated BLEVE and superheated BLEVE. To explain the difference between the two types, a definition of 'superheat limit temperature (SLT)' is introduced for the temperature limit, referring to the highest temperature at which superheat liquid (i.e., liquid excess of its boiling point) remains in the liquid phase without undergoing a phase transition at constant pressure (Avedisian, 1985). If the failure temperature is below the SLT, only vapour expansion generates energy to contribute blast waves, called "non-superheated" BLEVE. However, when the failure temperature is above the SLT, both vapour expansion and liquid flashing can contribute to energy for blast waves due to a very violent phase transition occurring, known as "superheated" BLEVE (CCPS, 2011; Eckhoff, 2014; Wang et al., 2022a).

To predict BLEVE loads, two methods are commonly used, i.e., energy equivalence method and numerical simulation. Energy equivalence methods refer to empirical models based on diverse thermodynamic assumptions, energy principles, and TNT charts (UFC, 2008). However, since the pressure-time history of TNT explosion rises instantaneously with an extremely short duration, the prediction method based on TNT charts may result in an inaccurate BLEVE load profile, leading to inaccurate structural response prediction. With the development of BLEVE models in recent years by Hansen and Kjellander (2016), Hutama (2017), and Li and Hao (2020), CFD simulations (i.e., FLACS) become a reliable method for predicting BLEVE wave propagation as the complex geometries and conditions can be modelled in detail in three dimensions. In addition, with the generated data from CFD simulations, machine learning approaches such as Artificial Neural Network (ANN) and Graph Neural Network (GNN) were employed to predict BLEVE wave propagation (Li et al., 2023a, 2023b, 2024) to overcome the limitations of high demand on computer powers with the traditional CFD models. Empirical models were also proposed to further simplify the prediction of BLEVE pressures for use in design analysis of structures against BLEVE (Wang et al., 2022a). It should be noted that FLACS is only applicable to predict the BLEVE occurring in open space and BLEVE wave interaction with rigid structures (Gexcon, 2022). Therefore, in a previous effort by the authors in predicting BLEVE loads on structures, the structure is assumed as rigid (Wang et al., 2023). An important point to consider is that rigid structure assumption is commonly adapted in modelling blast wave interactions with structures for predictions of blast load acting on structures. This assumption is reasonable because the duration of pressure wave from high explosives such as TNT is very short, in an order of mini seconds, during which structure has no time to deform. Shi et al. (2007) investigated the interaction of TNT blast wave with structures, and found that varying structural stiffness has insignificant influences on wave structure interaction, even a very flexible structure did not experience prominent deformation during the action of blast wave on the structure. Therefore, the structure behaved like a rigid one during the wave-structure interaction. This assumption, however, may not be applicable to BLEVE wave interaction with structures because of the relatively long duration. The duration of BLEVE wave is usually in the order of 10 ms, or even up to more than 100 ms, which is comparable to the fundamental vibration period of some structures and structural components, such as walls and columns. The deformation of structures during the action of BLEVE wave then would significantly affect the wave-structure interaction, hence the blast loads acting on the structure. Therefore, it is necessary to explore alternative CFD software, which has the capability to model BLEVE propagation and FSI of BLEVE wave interaction with deformable structures. So far, the studies on the interaction of BLEVE waves with structures are very limited, especially for structures of different stiffnesses that deform prominently during the action of BLEVE pressure wave.

In this study, FLACS is employed to predict BLEVE occurrences in open space and obtain the corresponding pressure-time profiles. Subsequently, the obtained pressure-time profile in open space is applied to ANSYS workbench as input. BLEVE wave propagation is simulated using ANSYS Fluent, coupled with ANSYS Mechanical (utilizing transient structural analysis) to simulate BLEVE wave interaction with deformable structures of different structural stiffnesses to determine the BLEVE loads acting on structures.

2. Numerical validation and modelling

2.1. BLEVE simulation by using FLACS

FLACS is a widely used computational fluid dynamics (CFD) tool for the safety evaluation of industrial accidents, including vapour cloud explosion, hydrogen safety, detonation of condensed explosives, and blast wave propagation, etc. (Gexcon, 2022). Reynolds-averaged Navier-Stokes (RANS) equations are applied by invoking the ideal gas equation of state and standard $k-\varepsilon$ model for turbulence (Launder and Spalding, 1983). To model condensed explosives and blast wave propagation, the Euler equations with flux-corrected transport (FCT) scheme and a second-order flux correction are employed (Boris and Book, 1973).

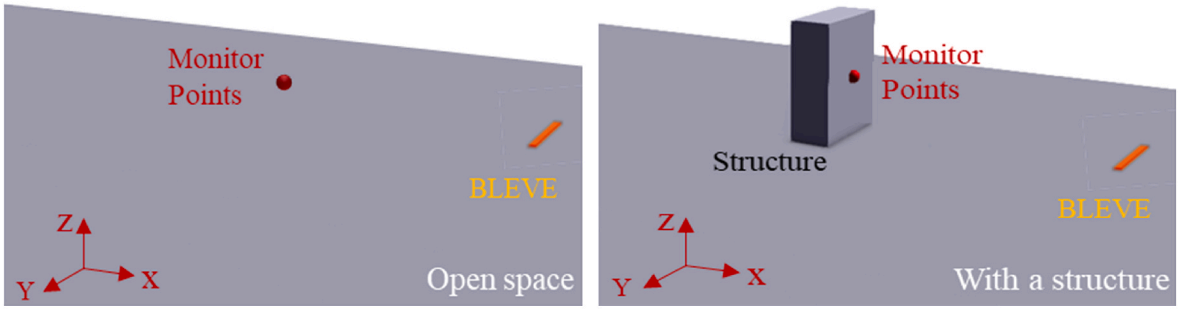
In the modelling, BLEVE is categorized into "non-superheated" and "superheated" based on failure temperature. In addition to BLEVE energy provided by vapour expansion, liquid flashing also contributes energy to the "superheated" BLEVE. Since FLACS cannot simultaneously model two high pressure regions, the liquid correction method is used to model the liquid high pressure region by introducing a pseudo-source to calculate the failure BLEVE pressure (Li and Hao, 2020). This study focused on the BLEVEs induced by LPG (i.e., butane and propane). The authors (Wang et al., 2022b) have demonstrated that FLACS simulations can predict LPG-induced BLEVE overpressure in open space with the error less than 25% by comparing with experimental data (Johnson and Pritchard, 1990; Birk and VanderSteen, 2006; Birk et al., 2007). The 0.2 m grid size in three directions (i.e., x-, y- and z-directions) is selected to balance the prediction accuracy and efficiency. Meanwhile, BLEVE tank is simplified as rectangular to minimize the mass residual problem due to the block control volumes of grid meshing in FLACS.

Previous studies (Wang et al., 2022a, 2023; Li and Hao, 2021) have verified that the FLACS can also well predict BLEVE loads on the rigid structure. The FLACS models of BLEVE in open space and BLEVE loads acting on a rigid structure are shown in Fig. 1. This study primarily addresses the prediction of the pressure-time profile resulting from a BLEVE on a flexible structure, which is more practical in the real world. However, the structure is set rigid and its material properties cannot be changed in FLACS software. Therefore, in this study, both ANSYS Fluent module and ANSYS Mechanical module in ANSYS Workbench are employed to simulate the BLEVE loads on a flexible structure.

2.2. BLEVE wave–structure interaction by using ANSYS workbench

2.2.1. Method selection

To study how the structural deformation affects the wave-structure interaction during the action of BLEVE wave, it is necessary to simulate the blast wave propagation and its interaction with the structure in CFD software. When investigating the interaction between BLEVE wave and structure, in addition to the condition of BLEVE source, the structural stiffness is another critical parameter to affect the reflected BLEVE waves. ANSYS Workbench can be used for the simulations. It is worth noting that ANSYS Workbench is unable to model the BLEVE. However, the blast pressure-time profile from FLACS can be applied to the boundary of ANSYS Fluent model as input to simulate BLEVE wave propagation and wave-structure interaction. In other words, the initial BLEVE pressure profile can be simulated by FLACS and extracted as an input load applied onto the boundary of ANSYS Fluent model in ANSYS Workbench, and the simulation of interaction of BLEVE waves with flexible structure can then be performed. To predict the BLEVE wave and structure interaction, a partitioned approach is employed. Namely, two solvers (i.e., ANSYS Fluent and ANSYS Mechanical APDL) are applied to simulate the blast wave propagation and structural response, respectively.



(a) (b)

Fig. 1. FLACS model: (a) BLEVE in open space; (b) BLEVE acts on a structure.

In terms of ANSYS Fluent, it lacks a specific explosive algorithm or subroutine for solving the blast-related problem (Sohaimi et al., 2016). Nevertheless, the software is good at solving complex fluid dynamics problems, allowing users to analyse and predict fluid behaviour in various scenarios (Fluent, 16.0). When BLEVE waves interact with a structure, the structure response should be further investigated by ANSYS Mechanical (Mechanical_APDL, 16.0). To solve the FSI problems, two approaches, namely one-way coupling and two-way coupling, are considered. For one-way coupling method, the results of the ANSYS Fluent module are used as inputs or boundary conditions to the Static Structural module. Although this method can save computational time, it neglects the effect of structural deformation on the blast wave due to no feedback loop between the two modules. In contrast, two-way coupling approach considers the interaction and feedback between the fields or physics being simulated. The simulation of the blast wave propagation in ANSYS Fluent and the structural analysis in the Transient Structural module can be connected into a loop through System Coupling and iteratively exchange information with each other during the simulation process. The BLEVE waves in the fluid flow simulation affect the structure, and in turn, the deformation of the structure affects the reflected blast waves. This bi-directional exchange of information continues until a converged solution is reached. The two-way coupling scheme considers the influence of the deforming structure on the fluid and can also guarantee energy conservation at the interface (Travanca and Hao, 2017; Benra et al., 2011). Therefore, a two-way coupling is adopted in this study to consider the response of the structure to the blast wave reflection.

2.2.2. Model validation

In terms of two-way coupling method, ANSYS Fluent module and Transient Structural module are combined by System Coupling. The BLEVE wave propagation is simulated by ANSYS Fluent. The density-based solver and transient solution are employed to solve the governing equation of continuity, momentum and energy in the coupled-implicit formulations. The energy equation model and standard $k-\varepsilon$ model with standard wall functions are applied. The gravitational acceleration in the z-direction is set. The ideal gas model is chosen for the air domain. The initial gauge pressure of 0 Pa as the reference operating pressure, and the blast pressure-time profile is applied as the pressure-inlet boundary condition of the air domain. A User Defined Function (UDF) is employed to import the pressure-time profile. The BLEVE overpressure data in open space obtained from FLACS is compiled as a UDF file. The pressure waves propagate normally to the boundary. Advection Upstream Splitting Method (AUSM) is chosen to provide the exact resolution of contact and shock discontinuities for convective flux calculation (Liou and Steffen, 1993). For the spatial discretization schemes, the least squares cell-based method is employed to evaluate the gradient, second order upwind is applied for flow, turbulent kinetic energy and dissipation rate calculation. Default relaxation factors are used in solution control. Subsequently, the structure is modelled with the Transient Structural module. The bottom of the structure is fixed on the ground, and the other surfaces of the structure are set as fluid-solid interfaces. The structure has various stiffness and the material properties are specified. Finally, the FSI problem can be solved by transferring and integrating the results of BLEVE wave pressure and structure simulation through System Coupling.

In the literature, there are no conducted BLEVE experiments in obstructed environments. However, FLACS has demonstrated its capability to accurately predict the BLEVE load acting on a rigid structure (Wang et al., 2023). The accuracy of ANSYS Workbench in predicting the BLEVE wave-structure interactions can be compared with the results from FLACS. The flowchart illustrating the simulation process from FLACS to ANSYS, and the finite element model employed for simulating the BLEVE wave-structure interaction in ANSYS are shown in Fig. 2. The grid sensitivity study is performed in ANSYS Workbench using the mesh sizes of 0.4m, 0.2m, 0.1m and 0.05m to simulate BLEVE wave interaction with a flexible structure, as depicted in Fig. 3. The difference in reflected peak overpressure between the 0.05 m and 0.1 m grid sizes is only 4.9%. However, the computational time increases exponentially if the grid size is reduced from 0.1 m to 0.05 m. Therefore, a mesh size of 0.1m is used to achieve the best trade-off between computational accuracy and efficiency. To illustrate the prediction accuracy in ANSYS Fluent, an example is employed. A BLEVE scenario is simulated using FLACS in a 2 m^3 pressurized storage tank with a rupture pressure of 18 bar. The reflected pressure at the front centre of a rigid structure situated 20 m away is monitored. At the same time, the pressure-time profile of BLEVE at 10 m in open space is simulated and extracted as input for ANSYS Fluent, and further coupled with ANSYS Mechanical to monitor the reflected overpressure at the front centre of the structure wall. Fig. 4 shows a close agreement in reflected peak overpressure, with 1.15% difference between the results obtained from ANSYS and FLACS, indicating the two-way coupling in ANSYS Workbench can accurately simulate the BLEVE wave propagation and FSI. Therefore, this approach is employed in the subsequent simulations.

3. Reflected BLEVE positive pressure

Structural stiffness and incident BLEVE wave duration are two critical factors, which have a significant effect on the interaction between blast wave and structure when considering the structural deformation during the action of BLEVE wave. This section conducts an in-depth analysis of their influence on the reflected BLEVE pressure.

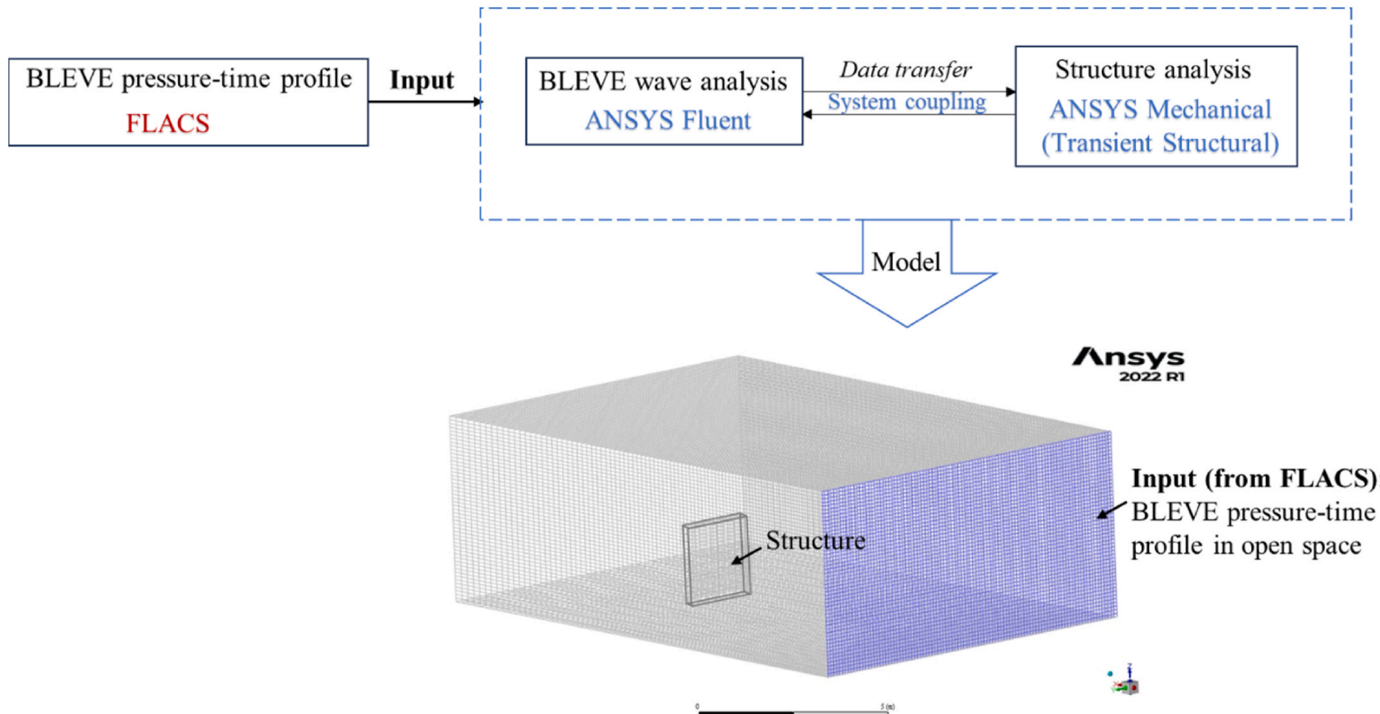


Fig. 2. Schematic diagram of the whole simulation process and finite element model in ANSYS.

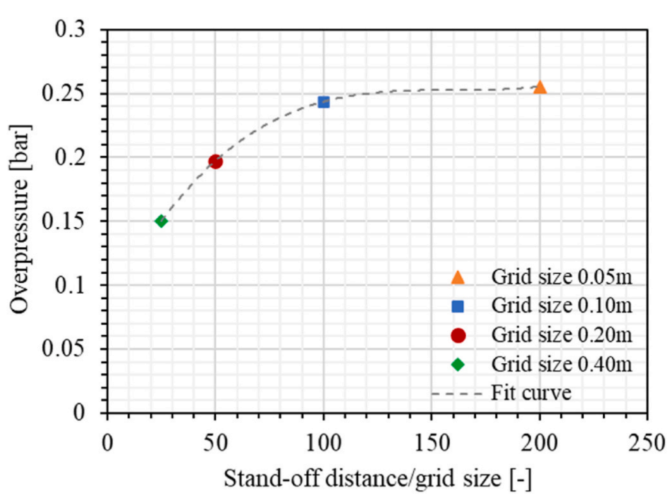


Fig. 3. Mesh convergence study in ANSYS.

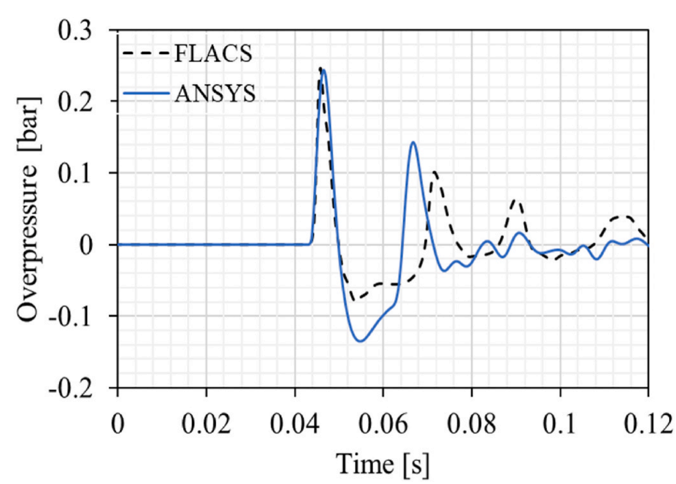


Fig. 4. Comparing ANSYS and FLACS prediction of BLEVE reflected pressure-time profile.

3.1. Effect of the structural stiffness

A previous study (Shi et al., 2007) has shown that structural deformation has minimal effect on wave structure interaction for high explosive explosions, even on a very flexible structure. This is due to the fact that TNT explosion typically has an extremely short duration, i.e., in the order of a few milliseconds, and thus the structure does not have a prominent deformation during the action of blast wave on the structure. However, the duration of BLEVE pressure wave is much longer than that of high explosive pressure wave. Therefore, the conclusion from Shi et al. (2007) may not be applicable to the scenario of BLEVE wave interaction with structures, since the longer duration of BLEVE could provide sufficient time for structure to deform during the action of BLEVE wave, which affects the reflected pressure-time profile. Therefore, the BLEVE loads on a flexible structure should be analysed by considering the effects of structural deformation.

To determine the effect of structural stiffness on BLEVE reflected pressure-time profile, numerical simulations are carried out. A BLEVE is firstly simulated in FLACS considering a 2.5 m^3 pressurized tank at a failure pressure of 41 bar. The pressure-time profile at a distance of 3 m away from the BLEVE centre is extracted as an input load applied onto the boundary of ANSYS Fluent model with a structure of dimension 1.5 m in width, 1 m in height and 0.1 m in thickness in the model as shown in Fig. 2. To study the influences of structural stiffness on the BLEVE wave-structure interaction, several cases with the structural stiffness of rigid, 10^7 N/m, 10^6 N/m and 10^5 N/m are considered in the simulations. The stand-off distance between the BLEVE centre and the front centre of the structure is 3 m. The generated blast loads on structures are compared in Fig. 5, which depicts the variations in reflected peak overpressure, duration and the pressure rise rate with respect to structures of different stiffnesses. The reflected peak overpressure and pressure rise rate for each case are given in Table 1. As shown, a stiffer

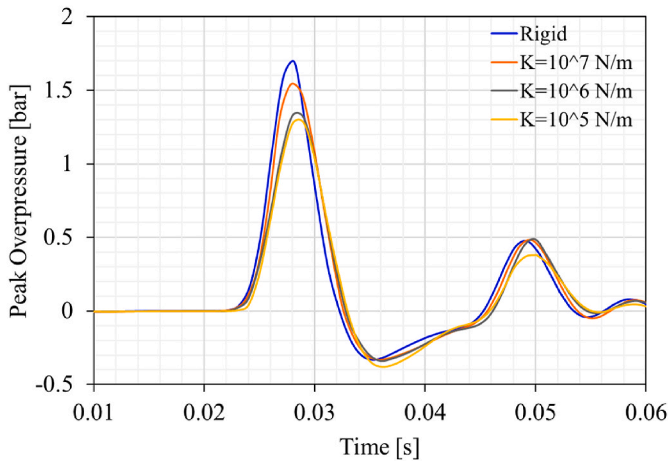


Fig. 5. Reflected pressure-time profile from structures of different stiffnesses.

Table 1
Reflected peak overpressure and pressure rise rate for each case.

Stiffness	Reflected peak overpressure P_r^+ [bar]	Pressure rise rate R_p^+ [bar/s]
Rigid	1.69	272.50
$K = 10^7 N/m$	1.54	263.20
$K = 10^6 N/m$	1.33	221.35
$K = 10^5 N/m$	1.28	213.81

structure results in a higher reflected peak overpressure. Decreasing the stiffness of the structure leads to a reduction in the peak reflected overpressure. With lower structural stiffness, the structure is susceptible to larger deformation, which reduces the pressure reflection. Moreover, larger structural deformation indicates more BLEVE pressure wave energy is converted to kinetic energy associated with structural response. It should be noted that plastic deformation and structural damage are not considered in the simulation. Therefore, there is no energy absorption. In reality, energy absorption owing to plastic deformation and structural damage would further reduce the reflected pressure wave if it occurs during the action of the BLEVE wave. Additionally, structural deformation also prolongs the duration of the BLEVE wave and structure interaction, hence resulting in slightly longer duration of reflected pressure wave. This phenomenon is the result of the enhanced energy transfer and coupling between the blast wave and the flexible structure, leading to a prolonged interaction time and thus a longer duration of the reflected blast wave. The corresponding pressure rise rate of the reflected pressure also slows down because of the structural deformation. This significantly reduces the loading rate and hence the structural response strain rate, which may lead to changes in structural response mode and damage mechanism.

As structural stiffness increases, the structural natural vibration period (T) decreases. To enhance the applicability of the analysis and facilitate meaningful conclusions about the blast wave-structure interaction in various scenarios and structures, the dimensionless ratio of the positive duration of blast load (t_d) to the structural natural vibration period is chosen as the parameter to quantify the BLEVE wave-structure interaction. When the positive duration of BLEVE wave is shorter than the structural natural vibration period (i.e., $t_d/T < 1$), the variation in structural stiffness significantly affects the coupling between the blast wave and structure. Specifically, reducing structural stiffness can amplify the dynamic response (Teich and Gebbeken, 2012; Xue et al., 2018), which leads to smaller peak reflected pressure, implying significant BLEVE wave-structure interaction effect. On the other hand, if t_d/T is large, corresponding to a small T or a stiff structure, the BLEVE wave-structure interaction effect is less prominent since the structural deformation is small.

In this study, the dimensions of the considered structural model are 1m width, 1m length and 0.1m thickness, with the structural stiffness ranging from 5×10^4 N/m to rigid (infinite). The incident duration (t_d) is chosen as 0.0145 s, which is the typical incident BLEVE duration from the experiment (Stawczyk, 2003). Fig. 6 illustrates that the reflected peak overpressure increases with the increased structural stiffness (i.e., reduced T and increased t_d/T since t_d remains unchanged). When the t_d/T is larger than 2.0, the reflected peak overpressure becomes stabilized, further increase in the t_d/T ratio has insignificant effect on the reflected peak pressure, implying the structural deformation has minimum effect on the BLEVE wave-structure interaction because the deformation of a stiff structure is small. When the $t_d/T < 1$, the coupling between the blast wave and the structure has considerable influence. This is because a reduced stiffness leads to higher flexibility, making the structure more susceptible to deformation under the blast wave, and the BLEVE wave-structure interaction pronouncedly affects the reflected pressure wave. Besides the relief of wave reflection owing to structural deformation, the increased flexibility enables more energy transfer between the blast wave and the structure, resulting in more obvious coupling. At the same time, the increased coupling allows the structure to undergo more pronounced dynamic responses, further mitigating the reflected peak overpressure. On the other hand, a stiff structure corresponds to small structural deformation, especially during the phase of BLEVE wave acting on the structure, energy transfer and coupling between them are greatly weakened, resulting in a less pronounced effect on the reflected peak overpressure. The present results indicate when T is 0.5 t_d or less, the structural deformation can be neglected in modelling the BLEVE wave-structure interaction.

3.2. *Effect of the incident BLEVE wave duration*

Besides the structural stiffness, the duration of the incident BLEVE wave is another key factor affecting the wave-structure interaction and subsequently the reflected pressure-time profile. In this section, the effect of incident blast wave duration on the positive reflected peak overpressure ($P^+_{r,flex}$) is discussed.

The incident duration is chosen to range from 0.01 to 0.08s, which covers the observed positive BLEVE pressure time histories in experimental tests (Birk et al., 2007; Stawczyk, 2003; Balke et al., 1999; Johnson and Pritchard, 1990). Based on the above model, the reflected peak overpressure under incident blast wave of different durations is compared in Fig. 7. Since the incident BLEVE wave duration has a significant influence on peak overpressure, the results are categorized into

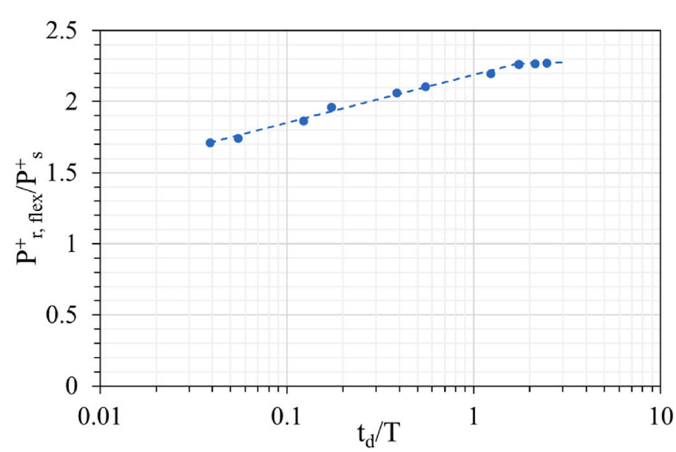


Fig. 6. The ratio of the positive reflected peak overpressure ($P^+_{r,flex}$) to incident peak overpressure (P^+_s) versus t_d/T.

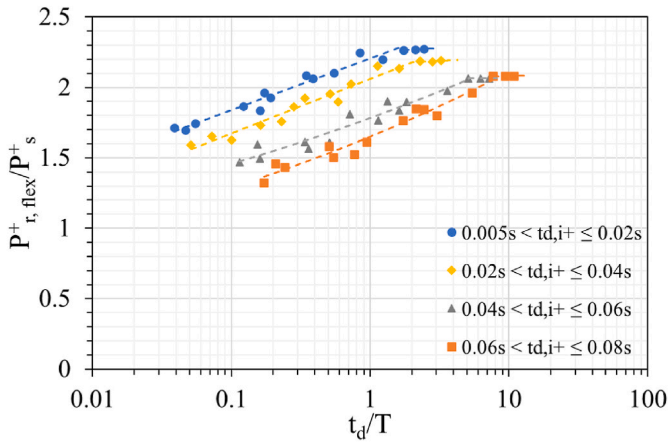


Fig. 7. The ratio of the positive reflected peak overpressure ($P^+_{r,flex}$) to incident peak overpressure (P^+_s) versus t_d/T for various incident duration ranges.

four specific ranges (i.e., 0.005–0.02s; 0.02–0.04s; 0.04–0.06s; 0.06–0.08s) based on the incident BLEVE wave duration. The pressure ratio ($P^+_{r,flex}/P^+_s$) can be determined using the fitted line corresponding to a specific range. As the incident BLEVE wave duration increases, the interaction between the blast wave and structure can become more significant. The blast wave interacts with the structure for an extended period, providing enough time for structure to deform and hence affects the BLEVE wave-structure interaction. This extended coupling time allows for a more complex energy transfer between the wave and the structure, potentially resulting in a more significant interaction and influencing the dynamic response of the structure, as well as leading to the variation in the reflected pressure-time profile. More energy transfer leads to a gradual decrease in the intensity of the reflected wave, resulting in a modified pressure-time profile. As a result, the peak overpressure is smaller, and the pressure rise rate during the reflection phase may be slower. However, when the incident BLEVE wave duration is long enough, the reflected peak pressure stabilizes at a relatively constant level. On the contrary, a shorter duration of incident BLEVE wave would result in a shorter coupling time between the wave and the structure, and make the BLEVE wave-structure interaction effect less prominent. This limited interaction time may lead to a more sudden and intense reflected pressure-time profile with a higher peak overpressure and a faster pressure rise rate, similar to the pressure wave interacting with a rigid structure.

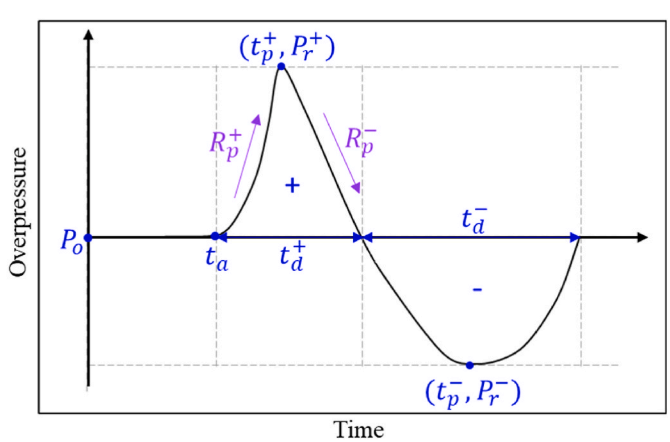


Fig. 8. Typical BLEVE overpressure-time profile.

4. Reflected negative peak pressure, duration and peak pressure rise time

Reflected positive pressure has been studied in Section 3. As shown in Fig. 8, other parameters, such as the reflected negative peak pressure (P^-_r), duration (t^+_d & t^-_d) and peak pressure rise time (t^+_p & t^-_p) are essential parameters to determine the reflected pressure-time profile of BLEVE load on structures, which are discussed in this section.

4.1. Reflected negative peak overpressure

Following the positive pressure phase, the blast wave enters a period where the pressure transitions to a negative phase. It is widely recognized that negative overpressure can create a suction force, the magnitude of the negative pressure arising from gas explosions is considerably smaller when compared to the positive overpressure (Karlos and Solomos, 2013; Hidallana-Gamage et al., 2017). The BLEVE negative peak overpressure on a rigid structure has been studied by the authors (Wang et al., 2023). The negative reflected peak overpressure (P^-_r) on a rigid structure can be calculated by Equation (1) (Wang et al., 2023). Fig. 9 compares BLEVE negative overpressure on the flexible and rigid structure, showing both structural stiffness and blast wave duration have little effect on the reflected peak negative pressure.

$$P^-_r = -0.26P^+_r - 0.059\ (bar) \quad (1)$$

4.2. Reflected overpressure duration

The overpressure duration is a critical factor in assessing structural response (Marjanishvili and Alsharkawi, 2020; Karlos and Solomos, 2013). The duration of the blast wave is determined by measuring the time from the point when the pressure commences increasing or decreasing from zero to the point at which the pressure reverts to atmospheric levels (CCPS, 2011). Fig. 10 shows the ratio of the positive reflected wave duration ($t^+_{d,flex}$) to the incident positive wave duration ($t^+_{d,i}$) with respect to t_d/T ratio. It can be seen that a more flexible structure and/or BLEVE wave with a longer duration t_d are associated with more pronounced coupling during the wave-structure interaction, which results in a longer positive duration of the reflected pressure-time profile, but has little effect on the negative duration of the overpressure.

4.3. Reflected peak pressure rise time & pressure rise rate

The pressure rise rate is another key factor to be considered in the structural response analysis. When blast wave reaches the peak positive and negative overpressure, the corresponding time is referred as peak

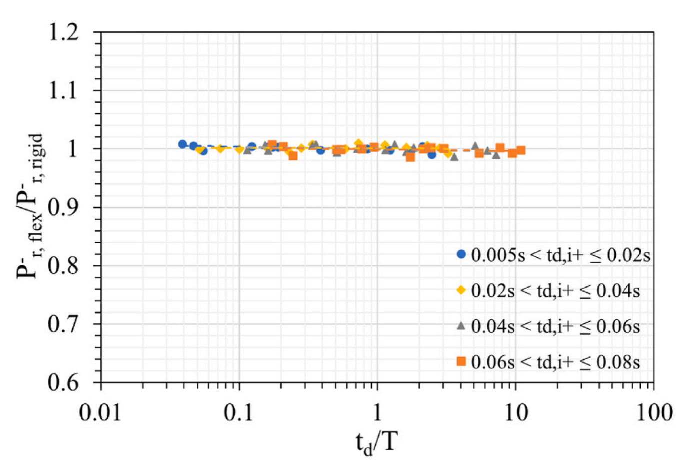
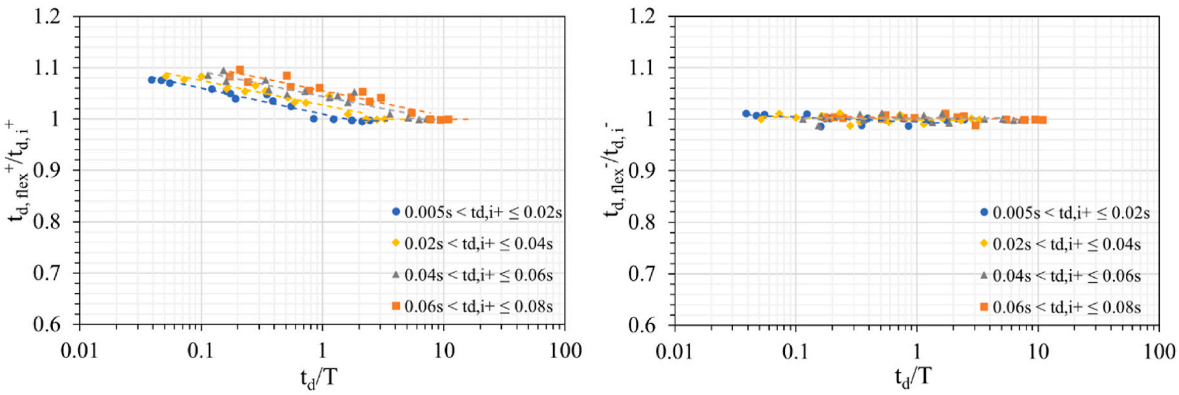


Fig. 9. The ratio of the negative reflected peak overpressure on flexible structure ($P^-_{r,flex}$) to rigid structure ($P^-_{r,rigid}$) versus t_d/T.



(a) (b)

Fig. 10. The ratio of the reflected duration ($t_{d,flex}$) to incident duration ($t_{d,i}$) versus t_d/T: (a) Positive ($t^+_{d,flex}$); (b) Negative ($t^-_{d,flex}$).

pressure rise time (t^+_p & t^-_p) in pressure-time profile as shown in Fig. 8. The pressure rise rate (R_p) can be obtained by calculating the ratio of the peak overpressure to the rising time (i.e., peak pressure rise time t^+_p– arrival time t_a).

To determine the reflected peak pressure rise time owing to the interaction with flexible structures ($t^+_{p,flex}$ & $t^-_{p,flex}$), they are calculated and compared with the incident peak pressure rise time ($t^+_{p,i}$ & $t^-_{p,i}$), as shown in Fig. 11. The findings indicate that $t_{p,flex}$ and $t_{p,i}$ are very similar, implying that the structural stiffness and incident blast wave duration have minimal influence on the reflected peak pressure rise time. While various structural stiffness values and incident wave durations do not affect the reflected peak pressure rise time, the flexible structure or longer incident duration leads to a reduced reflected peak overpressure in comparison to the rigid structure or BLEVE wave with shorter durations, thereby contributing to a slower pressure rise rate. The ratio of the reflected pressure rise rate ($R^+_{p,flex}$) to the incident pressure rise rate ($R^+_{p,i}$) is depicted in Fig. 12.

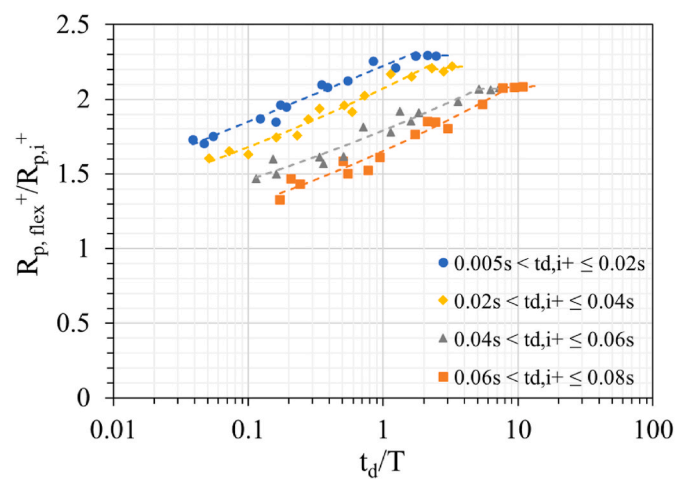
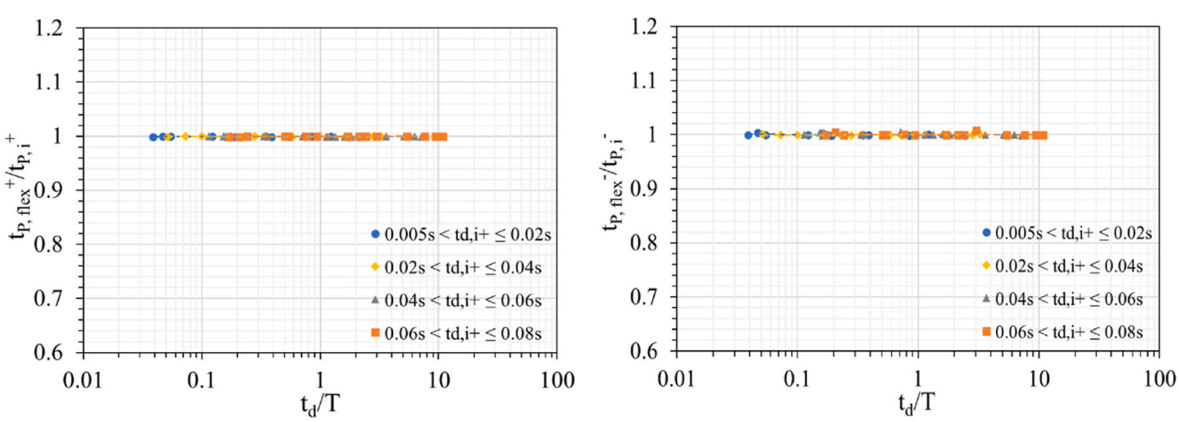


Fig. 12. The ratio of the reflected pressure rise rate ($R^+_{p,flex}$) to incident pressure rise rate ($R^+_{p,i}$) versus the ratio of t_d/T.



(a) (b)

Fig. 11. The ratio of the reflected peak pressure rise time ($t_{p,flex}$) to incident peak pressure rise time ($t_{p,i}$) versus the ratio of t_d/T: (a) Positive ($t^+_{p,flex}$); (b) Negative ($t^-_{p,flex}$).

5. Case study

To predict the BLEVE reflected pressure-time profile on a flexible structure, the charts given in Sections 3 and 4 can be used along with the results reported in the previous study, i.e., BLEVE overpressure in open space (Wang et al., 2022a). In this section, a case study is provided to elucidate the prediction process.

The BLEVE test No. 02-1 by Birk et al. (2007) is employed as an example here. The BLEVE tank has a volume of 2 m^3. It contains liquified propane with a fill ratio of 51%. BLEVE occurs at pressure up to 18 bar, and the liquid and vapour temperature reach 330 K and 334 K, respectively. Assuming that the dimensions of the cantilever flexible structure are 3 m in width (W_{str}), 3 m in height (H_{str}) and 0.4 m in thickness (L_{str}), along with a density (ρ) of 2400 kg/m^3, a Young's Modulus (E) of 3×10^{10} Pa, and a Poisson's ratio (v) of 0.3. The stand-off distance between the BLEVE centre and the front centre of flexible structure is 20 m. The predicted reflected BLEVE wave profile on the flexible structure is given below. The schematic diagrams of BLEVE occurring in open space and BLEVE load on a structure are shown in Fig. 13.

In the previous study conducted by the authors (Wang et al., 2022a), the peak overpressure (P_s^+ & P_s^-), duration (t_d^+ & t_d^-), arrival time (t_a) and peak pressure rise time (t_p^+ & t_p^-) for BLEVE in open space are calculated and listed in Table 2.

When analysing the effects of BLEVE loads on a flexible structure, it is necessary to incorporate structural stiffness into the calculations. This inclusion is essential in assessing how structural stiffness affects the characteristics of the reflected pressure wave, therefore enabling the accurate prediction of the reflected pressure-time profile. The structure stiffness in this case study is calculated as follows.

The moment of inertia I:

$$I = \frac{W_{str} {L_{str}}^3}{12} = 0.016\ m^4 \tag{2}$$

The stiffness of the structure:

$$K = \frac{3EI}{{L_{str}}^3} = 5.33 \times 10^7\ N\Big/m \tag{3}$$

The structural natural vibration period:

$$T = 2\pi\sqrt{\frac{m}{K}} = 2\pi\sqrt{\frac{3 \times 3 \times 0.4 \times 2400/2}{5.33 \times 10^7}} = 0.057\ s \tag{4}$$

Since the positive phase duration (t_d) of the incident wave is 0.0084s, the ratio of the positive wave duration to the structural natural vibration period is

$$\frac{t_d}{T} = 0.15 \tag{5}$$

The ratio of the reflected peak overpressure to incident peak overpressure can be obtained from Fig. 7 as

$$\frac{P^+_{r,flex}}{P^+_s} = 1.90 \tag{6}$$

Thus, the reflected positive peak overpressure:

$$P^+_{r,flex} = 1.90 \times 0.0813 = 0.155\ bar \tag{7}$$

The reflected negative peak overpressure can be calculated by Equation (1):

$$P^-_{r,flex} = -0.26P^+_{r,flex} - 0.059 = -0.099\ bar \tag{8}$$

Using Fig. 10 (a), the ratio of the duration of the reflected positive pressure to positive phase duration of incident wave is

$$\frac{t^+_{d,flex}}{t^+_{d,i}} = 1.05 \tag{9}$$

The reflected positive phase duration is

$$t^+_{d,flex} = 1.05 \times 0.0084 = 0.0089\ s \tag{10}$$

The reflected negative phase duration ($t^-_{d,flex}$), arrival time ($t_{a,flex}$) and peak pressure rise time ($t^+_{p,flex}$ & $t^-_{p,flex}$) are very similar to the incident ones, which are:

$$t^-_{d,flex} = t^-_{d,i} = 0.0111\ s \tag{11}$$

$$t_{a,flex} = t_{a,i} = 0.0488\ s \tag{12}$$

$$t^+_{p,flex} = t^+_{p,i} = 0.0526\ s \tag{13}$$

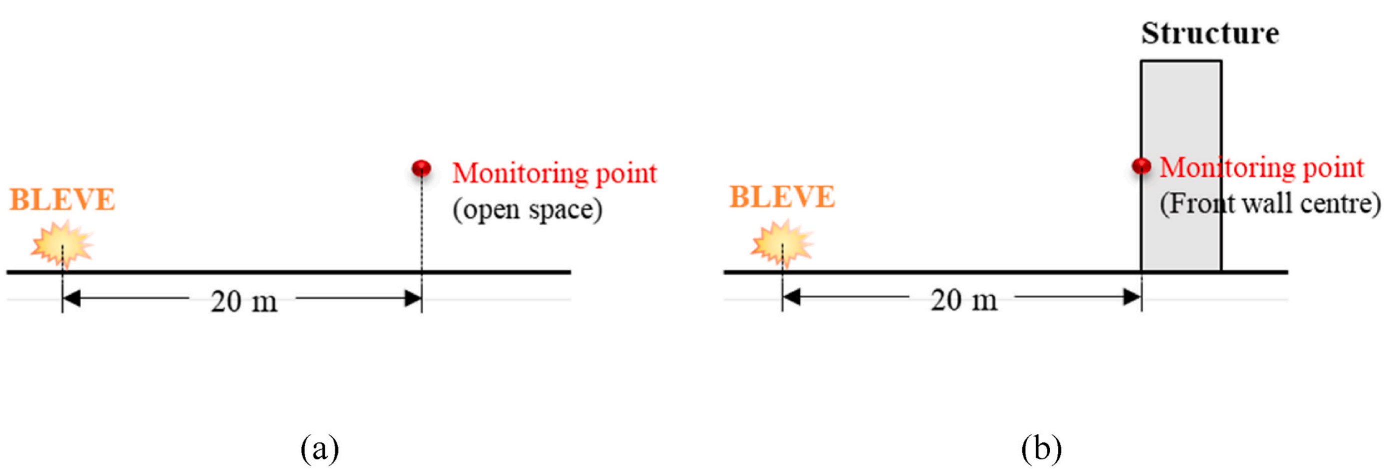


Fig. 13. Schematic diagram of BLEVE cases: (a) open space; (b) a structure in the area.

Table 2
Predicted BLEVE overpressure in open space (Wang et al., 2022a).

	P_s^+ [bar]	P_s^- [bar]	$t^+_{d,i}$ [s]	$t^-_{d,i}$ [s]	$t_{a,i}$ [s]	$t^+_{p,i}$ [s]	$t^-_{p,i}$ [s]
Open space	0.0813	−0.0600	0.0084	0.0111	0.0488	0.0526	0.0652

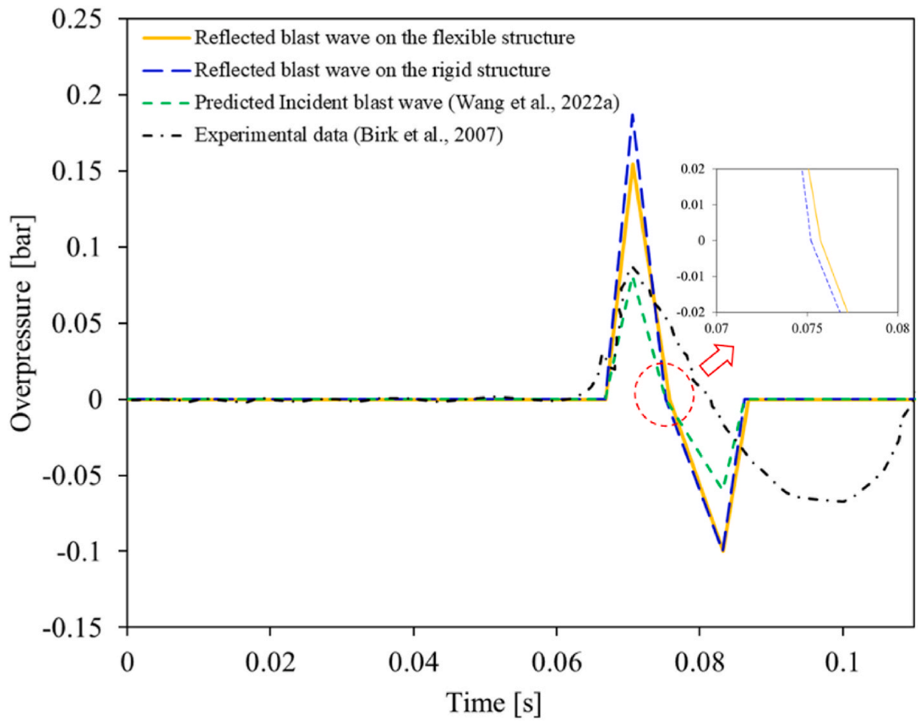


Fig. 14. Reflected pressure-time profiles (on the rigid and flexible structure) and incident pressure-time profiles (experimental (Birk et al., 2007) and predicted (Wang et al., 2022a)).

$$t^{-}_{p,flex} = t^{-}_{p,i} = 0.0652\ s \quad (14)$$

Fig. 14 presents the reflected overpressure on a flexible structure with the above calculated parameters and also compares it with the corresponding reflected pressure-time profiles on a rigid structure and the incident pressure-time profile when BLEVE occurs in open space (Wang et al., 2022a). The Birk et al. (2007)'s experimental data of recorded pressure-time history in open space is also included for comparison. The peak reflected overpressure on a flexible structure is around 20% less as compared to that on a rigid structure.

6. Conclusions

This study aims to predict the reflected pressure-time profile generated by a BLEVE on a flexible structure for reliable prediction of BLEVE loads on structures. The interaction of BLEVE waves with flexible structures is simulated by using ANSYS Fluent for the blast wave propagation coupled with ANSYS Mechanical for structural analysis. Based on the results obtained, the following conclusions can be drawn.

1. A more flexible structure with larger structural deformation during the action of BLEVE wave on the structure leads to a smaller peak reflected pressure and longer duration, i.e., a BLEVE load of smaller amplitude but longer duration acting on the structure.
2. Under the same structural stiffness, longer duration of the incident BLEVE wave leads to lower reflected peak overpressure. When the ratio of positive BLEVE wave duration to the natural period of the structure is small, the effect of BLEVE wave-structure interaction is prominent. Increasing the t_d/T ratio increases the peak reflected pressure. When t_d/T is larger than 2.0, further increasing the ratio has an insignificant effect on the reflected pressure, indicating the structural deformation can be neglected in modelling the BLEVE wave-structure interaction.
3. Structural stiffness and incident wave duration have little effect on the reflected negative pressure and reflected peak pressure rise time. However, as the structure becomes more flexible or the incident wave duration of the BLEVE wave increases, the pressure rise rate is slower due to a reduction in the reflected peak overpressure.

CRediT authorship contribution statement

Yang Wang: Writing – original draft, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Wensu Chen:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Hong Hao:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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