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# Counter-intuitive collapse of single-layer reticulated domes subject to interior blast loading

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ABSTRACT

A commercial finite element package, LS-DYNA, was employed to simulate the response of a single-layer reticulated dome to an interior blast. The dome, which was initially stressed by static preloading, encountered an interesting phenomenon namely counter-intuitive collapse, which was found during the blast analysis. The Johnson–Cook constitutive model for mild steel was used to identify different failure modes of the dome for more than 2430 samples. A seemingly counter-intuitive collapse was identified due to dynamic instability. This unusual collapse was explained using total potential curves, and the critical blast load was defined. The effect of different static preloads, which is the other determination factor of counter-intuitive collapse, was investigated. A relationship between collapse and static/dynamic loads was also obtained. The results indicate that single-layer reticulated domes, with large initial stresses, may collapse at lower dynamic loads than expected.

## 1. Introduction

An interesting dynamic phenomenon attracted the attention of Symonds and Yu, when they were conducting studies of a pin-ended beam subject to short pulse excitations [1,2]. This was the permanent deflection of the mid-point stays in the opposite direction to the load, which was called “counter-intuitive” behaviour. They used a number of well-known dynamic codes and a Shanley-type model to prove the existence of this phenomenon. Later, other researchers confirmed this behaviour experimentally [3,4]. Further surprising similar phenomena were found on other components during tests or in numerical simulations. These counter-intuitive behaviours were encountered in plates and rings as well as in shallow shells [5–8].

The majority of research into counter-intuitive behaviour has focused on single members. However, the potential hazard of counter-intuitive behaviour occurring in real structures has been neglected; and this is far more dangerous than for single members. During the study of the dynamic response of single-layer reticulated domes, an interesting failure mode occurred when the structures were subjected to interior explosions. Unlike the other cases, the whole structure deflected in the opposite direction to the blast loading and totally collapsed. Especially, sometimes the dome is just suffered a very small blast loading, which is far less than the failure level initially expected. It is clearly an example of counter-intuitive behaviour in the global structure, which must be paid more attentions.

To the authors' knowledge, the counter-intuitive collapse of single-layer reticulated domes has not been previously referenced. Zhi [9] distinguished two collapse modes for single-layer reticulated shells using the structural response of a large number of samples at their failure states. He pointed out that the dynamic instability of shell-type structures is a result of the geometric nonlinear effect, while strength failure is caused by severe plastic deformation of materials and plastic damage. Failure modes of the domes subject to impact were studied by Fan [10,11]. Four failure modes were presented, namely slight damage of a member, local failure of the dome, global collapse of the dome and shear failure of a member. The ultimate deformation of a single-layer Kiewitt-8 reticulated dome was also classified by the mass and velocity of an impactor. Lin considered the size and material properties of an impactor on the failure modes of single-layer Kiewitt-8 reticulated domes [12,13]. The analytical results indicated that the impactor size could change the failure modes of the reticulated dome.

In this paper, a numerical model of a single-layer reticulated dome with static preloading, was used to investigate its dynamic response when subjected to interior blast loading. Four failure modes were distinguished and the failure mechanisms explained. In particular, the alternate appearance phenomena of collapses were explained using total energy curves, and the critical blast impulse for dynamic instability was defined. Furthermore, varying initial statuses of the dome under different static preloads was

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compared to clarify that counter-intuitive collapse is a composite result of both the static and dynamic loads. Additionally, the dynamic responses for interior blast loads were divided into different zones for avoiding counter-intuitive collapse during the blast-resistant design period. Meanwhile, the findings from this study suggest an explanation of the counter-intuitive behaviour.

## 2. FE models of reticulated dome

As introduced previously, the counter-intuitive behaviour occurred in single-layer reticulated domes. The commercial finite element package LS-DYNA was used to model a reticulated dome subject to interior blast loads with a static preloading.

### 2.1. Two-step analysis process

During and following the construction, structures are naturally stressed and deformed by gravity. Therefore, stress initialisation is an essential procedure which should be taken into account in the analysis [14]. In the current study, the process of numerical modelling involves two independent parts: static preloading and blast loading.

The static preloading, which is 5 s long (Fig. 1a), was undertaken using the restart analysis of LS-DYNA. Keyword *Load_Body_Z was used to complete the stress initialisation process [15]. To avoid shock effects in the explicit environment, the gravity action was treated as a load curve which is ramped up to 9.81 m/s$^2$ slowly in the first 4 s. From the fifth second, the load curve was held constant with 9.81 m/s$^2$. A relative large damping was used only during the stress initialisation process to minimise the high frequency responses. These double ensured that the stresses in the dome were steady before the dynamic analysis was performed.

In the dynamic process, the blast loading was represented by a group of triangular loads [16–19]. Although the value of the triangular loads (Fig. 1b) was controlled by peak pressure and duration, the impulse is the crucial factor affecting structural response for structures with relatively long natural vibration periods [20,21]. In order to simplify the problem, the blast duration was fixed at 10 ms, which is small enough for the natural vibration periods of reticulated domes. Thus, the value of the impulse was actually controlled by the peak pressure $P_r$. The peak pressures are also assumed to have an uniform distribution at each joint, and the directions of impulses are chosen to be perpendicular to the reticulated dome (Fig. 2).

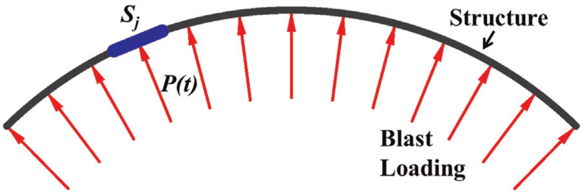

**Fig. 2.** Schematic diagram of interior blast loading.

### 2.2. Material

As blast loads occur for such as short time with a fast speed and generate large deformations in targets, the Johnson–Cook constitutive model for mild steel was adopted. The model is especially useful for metals subject to large strain, high strain rates and high temperatures [22]. The flow stress can be expressed by

$$\sigma = (A + B\varepsilon^{p^n})(1 + c\ln \dot{\varepsilon}^*)(1 - T^{*m}) \quad (1)$$

where $A$, $B$, $c$, $n$ and $m$ are constants; $\varepsilon^p$ is the effective plastic strain; $\dot{\varepsilon}^*$ is the effective strain rate and $T^*$ is the homologous temperature. However, thermal effects are not the main factor for the tubes with thin-walled cross-sections, especially in the far-field blast problems. Therefore, the simplified Johnson–Cook model in LS-DYNA was employed which is given by the following equation [15]:

$$\sigma = (A + B\varepsilon^{p^n})(1 + c\ln \dot{\varepsilon}^*) \quad (2)$$

In this equation, the thermal effect is ignored. The fracture is controlled by the given plastic strain.

Due to the entire reticulated dome are made by steel, the same material [23] was used to simulate all the components of dome in the FE model. The details are summarised in Table 1.

### 2.3. The FE dome model with roof system

The model of the single-layer Kiewitt 8 system reticulated dome is shown in Fig. 3. The whole span is 40 m divided into six rounds, with a 1/7 ratio of rise to span. All supports in the model are immovable with three-way hinged. The dome is composed of circular steel tubes which are connected by 169 welded hollow spherical joints. Each member in the dome was meshed to 3 beam elements with four integration points in the cross-section.

For more realistic, the steel roof panels were also set up. As shown in Fig. 4, the shape of each roof panel is triangular, which is as the same dimension as the area composed by three interconnection beams of dome. The size of each roof panel is varying

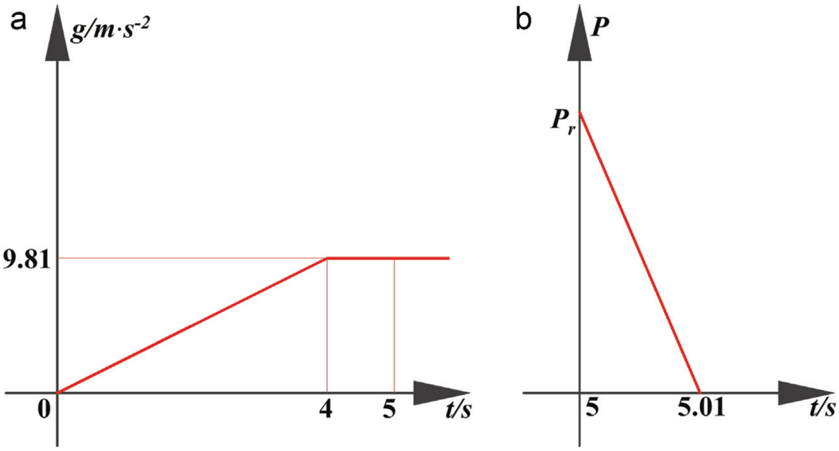

**Fig. 1.** Static and dynamic loads. (a) Static preloading (b) blast loading.