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Responses of curved steel-concrete-steel sandwich shells subjected to blast loading

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ABSTRACT

The blast response behaviors of curved Steel-Concrete-Steel (SCS) sandwich shells were investigated using nonlinear finite element method. The accuracy of the numerical model was verified against the available field blast test results. The numerical results showed that shear connectors played a vital role in bonding the face plates and concrete core and therefore improving the blast resistant capacity of curved SCS sandwich shell. In addition, different failure modes for the curved SCS sandwich shell under close- and far-field blast loading were observed, i.e., separation of rear plate from concrete core and buckling of face plates for the shell under close- and far-field blast loading, respectively. The effects of rise height (or rise to span ratio) and rear to front plate thickness ratio on the blast responses of curved SCS sandwich shells were also studied. Numerical results showed that the damage of curved SCS sandwich shell could be reduced by increasing rise height and rear to front plate thickness ratio. Moreover, the energy absorption efficiency of concrete core also showed increase with increasing rear to front plate thickness ratio.

1. Introduction

The curved Steel-Concrete-Steel (SCS) sandwich shell was initially developed for arctic caissons to resist impact force from moving ices, as shown in Fig. 1, and its punching resistance against concentrated load was also studied [1–3]. Besides this, the good performance of flat SCS sandwich shells against impact and blast loads was also demonstrated [4–12] and it is prior to the traditional concrete and steel shells in terms of high ductility, spalling protection, buckling resistance and energy absorption. The curved shell normally performs better than the flat shell under uniformly distributed loading by developing compressive force and reducing the bending moment. This superiority is significant for the curved SCS sandwich shell, since the compressive strength of concrete is much higher than the tensile strength. Hence, the curved SCS sandwich shell has potential application in resisting blast loading and Fig. 2 illustrates its application in blast wall. Due to the minimal reported works on the curved SCS sandwich shell under blast loading, the aims of this work are to study the blast response behaviors of curved SCS sandwich shell, including failure mechanism and mode, blast energy absorption, as well as geometric parameters that affect the blast performance of curved SCS sandwich shell. The findings from this work will help to understand the behavior of such structure under blast loading and also promote its application in resisting blast loading.

SCS sandwich shell consists of a concrete core connected to two external steel face plates using mechanical shear connectors. The composite action of a SCS sandwich structure is achieved through shear connectors to bond the two face plates to the concrete core. Several types of shear connectors have been developed, including headed shear studs [13], angle shear connectors [14], Bi-steel [15] and interlocked J-hook connectors [16]. The shear connectors in flat SCS sandwich shells have three main functions: (1) producing sufficient bond between face plates and concrete core; (2) providing longitudinal and transverse shear resistance and (3) preventing uplifting of top plate from concrete core. Hence, the shear connectors are vital for the flat SCS sandwich shell against static and dynamic loading. However, it was demonstrated by Kang that the flat SCS sandwich shells without shear connectors could perform as well as those with shear connectors, including headed studs and J-hook connectors [17]. This could be attributed to the utilization of side and end plates, which was functioned as shear connectors to achieve composite action between face plates and concrete core [18]. In this paper, the effect of shear connectors on the blast response of curved SCS sandwich shell was also

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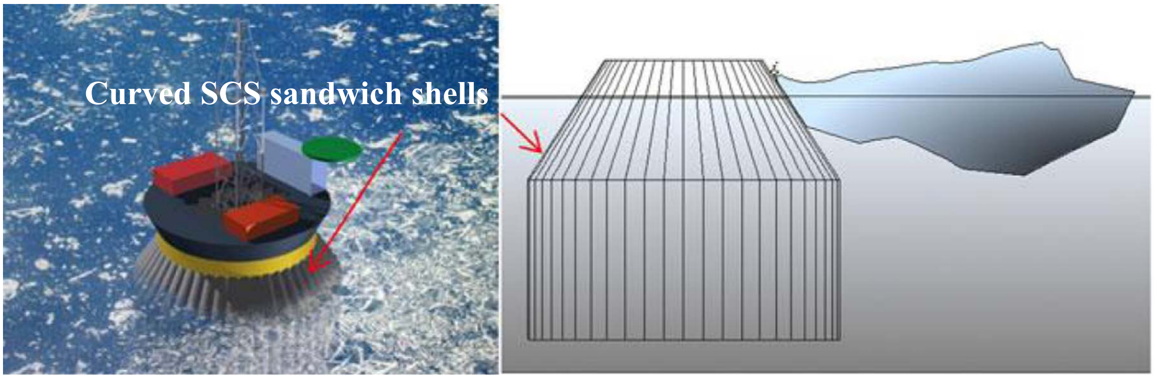

Fig. 1. Ice-resistant wall [2].

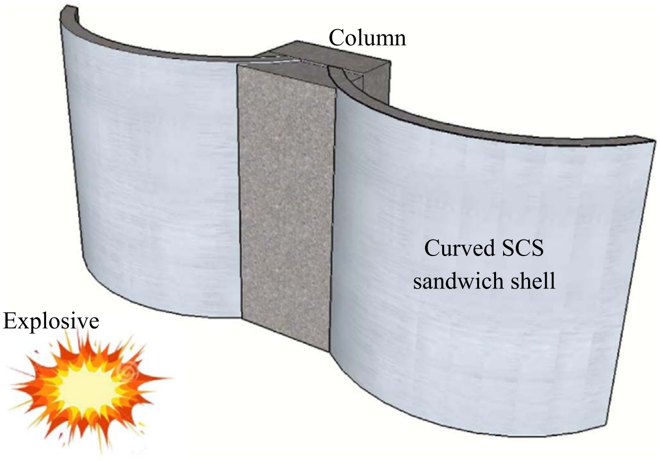

Fig. 2. Curved SCS sandwich shell as blast wall.

investigated.

The equivalent Single-Degree-of-Freedom (SDOF) method [19], which is a simple method to evaluate the response of continuous member under blast loading, has been widely adopted by blast resistant design guidelines [20–22]. The equivalent SDOF method is based on the energy conservation and can capture the global structural response. Hence, it is a relatively simpler alternative as compared to detailed Finite Element (FE) method and can yield acceptable predictions in most cases. Recently, FE method is increasingly adopted to predict the structure's response under blast loading and can yield more accurate predictions than the equivalent SDOF method. The explicit code in LS-DYNA, which has more than two hundred material models and is suitable for modeling structures under high rate loading, was widely adopted to simulate the blast response of civil infrastructure, including steel [23,24], concrete [25–30] and steel-concrete composite structures [8,10]. In this paper, the LS-DYNA was also adopted to simulate the curved SCS sandwich shells under blast loading.

In this paper, the FE model of SCS sandwich shell under blast loading was established and its accuracy was verified by comparing with field blast test results. The verified FE model was then used to study the failure mode of curved SCS sandwich shell without shear connectors. Since separation between face plates and concrete core was observed for the shell without shear connectors, the shear connectors were introduced to bond the face plates to concrete core and improve the blast resistance. The failure modes of curved SCS sandwich shell with shear connectors under close- and far-field blast loading were also obtained. Finally, the effects of rise height (or rise to span ratio) and rear to front plate thickness ratio on the blast response behaviors of curved SCS sandwich shell were studied.

2. Numerical model verification

2.1. FE model of flat SCS sandwich shell and verification

Since there is no available experimental data on curved SCS sandwich panel subjected to blast loading in published references, the field blast test conducted by Liew and Kang [10,31] on the flat SCS sandwich shell, which has similar configuration of curved SCS sandwich shell, was adopted to validate the FE model of curved SCS sandwich shell subjected to blast loading. The detailed FE modeling of flat SCS sandwich shell and the comparisons between FE and experimental results were presented in Ref. [8]. Hence, the FE model of flat SCS sandwich shell, including material models, element formulations and contact approaches, are briefly summarized as follows.

The Continuous Surface Cap Model (CSCM) in LS-DYNA [32] was adopted to simulate the behavior of concrete. The CSCM was originally developed by US Federal Highway Administration to simulate the concrete-like material subjected to impact and blast loading [33,34]. The detailed description of CSCM model, including failure surface, flow rule and strain rate effect treatment, etc., can be found form Ref. [33]. This material model is easy to use since it can generate the default parameters for the normal weight concrete by only inputting the unconfined compressive strength. The main parameters of concrete used in this analysis are given in Table 1. The Piecewise Linear Plasticity material model in LS-DYNA was adopted for the steel material. The material properties of steel were obtained from the tensile coupon test and the input true stress–effective plastic strain curve is shown in Fig. 3. The failure strain was defined as 0.2, i.e., the element with effective plastic strain exceeding 0.2 will be removed from the FE calculation. In this material model, the Cowper-Symonds model [35] is adopted to scales the yield stress as

$$\sigma_y\left(\varepsilon^p_{eff}, \dot{\varepsilon}^p_{eff}\right) = \sigma_y\left(\varepsilon^p_{eff}\right)\left[1 + \left(\frac{\dot{\varepsilon}^p_{eff}}{C}\right)^{1/P}\right] \tag{1}$$

where $\sigma_y\left(\varepsilon^p_{eff}\right)$ is the yielding stress without considering strain rate effects, $\dot{\varepsilon}^p_{eff}$ is the effective plastic strain rate, C and P are the strain rate parameters. In this study, the strain rate parameters C and P were 40.4 and 5 for mild steel [36]. The steel plates of flat SCS

Table 1
Material properties of concrete in FE analysis.

Density (kg/m^3)	Compressive strength (MPa)	Shear modulus (GPa)	Bulk modulus (GPa)
2310	35	12.06	13.21