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The energy-based failure mechanism of reticulated domes subjected to impact

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ABSTRACT

To systematically study and determine the failure mechanism of reticulated domes when subjected to impact, ANSYS/LSDYNA was utilized to establish a functional and effective finite-element analysis method for the impact responses of reticulated domes. The impact load characteristics imposed on reticulated domes under three types of failure modes were analyzed, and the peak value and duration time were compared. Based on structural deformation and the node velocity at critical moments during impact, the collapse of reticulated domes is classified into three stages in light of energy transfer and conversion: impulse application, energy transfer, and conversion and dissipation. On this basis, and using the single-layer Kiewitt-8 reticulated dome as an example, the characteristics of energy transfer and conversion of the impact-induced failure processes were quantitatively analyzed. Consequently, the energy-based failure mechanism of reticulated domes subjected to impact is revealed.

1. Introduction

With the wide application of large-span reticulated domes in prestigious large-scale public buildings, the behavior of reticulated domes subjected to accidental loads, such as impact and blasting, has become a focal point. Although impact load is categorized as an accidental load, its probability for occurrence has been increasing in recent years due to an increased threat of terrorist attacks and other causes. The most renowned such attack is the 9/11 incident. The design of the World Trade Center Twin Towers represents an advanced current design level, and it even survived the impact of a Boeing 707. However, the impact and its consequential action still led to structural progressive collapse. Furthermore, in the 1980s, a light aircraft fell into the roof truss of the Saint Paul Exhibition Center in Brazil, providing further evidence of the probability of flying objects impacting large-span structures.

Structural progressive collapse refers to local structural failure resulting from accidental load and consequently leading to chain reactions, which in turn cause the spreading of local failures to other parts of the structure. Ultimately, this causes global collapse of the structure, spreading from local to global failure. In general, if the final structural failure mode is not proportional to its initial state, such a failure is classified as a progressive collapse. Progressive collapse is one of the disastrous consequences caused by an accidental load (such as impact or blasting), and the occurrence of collapse under impact will result in serious negative social effects in addition to great loss of life and economical value [1]. Therefore, the research on collapse mechanisms of the global structure when subjected to impact seems of particular importance, and it has been a popular topic in structural engineering.

Wang et al. conducted extensive and systematic research on the failure modes of reticulated domes when subjected to impact, and they summarized and analyzed their failure rules via numerous parametric analyses [2]. Moreover, Wang and Lin examined whether different material models were suitable for finite-element analysis via a reduced-scale model impact experiment on reticulated domes [3,4]. Zhi et al. carried out research on impact-resisting defense methods for single-layer reticulated domes [5]. In addition, Tongxi et al. analyzed the causes for the dynamic collapse of the Twin Towers of the World Trade Center and proposed a theoretical model for progressive dynamic collapse of high-rise structures. This model used a straightforward energy analysis to note that in high-rise buildings (such as the Twin Towers of the World Trade Center), the dissipated energy caused by structural deformation and failure in the collapse process of each story is smaller than the released potential energy, and thus this high-rise building was indeed inherently unstable [6]. Seffen et al. also conducted simplified

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analyses on the collapse of the Twin Towers of the World Trade Center and established a simplified dynamic analysis model, taking into account the decrease of loading capacity. The use of this model produced good effects in the analysis of the progressive collapse of high-rise buildings [7]. Starossek et al. summarized different types of progressive collapse in structural engineering based on collapse mechanisms, and they classified progressive collapse into six types, including Story Domino Collapse and Mixed Collapse. This study provides a systematic and extensive summary in the field of the progressive collapse of structures [8–12]. Abedi and Parke examined the progressive collapse of single-layer reticulated domes, and concluded that hinge-connected single-layer reticulated domes are more susceptible to progressive collapse than rigid domes, as more kinetic energy is produced with hinge connections and that particular attention should be paid to this factor. Moreover, the analysis of this factor indicated that reticulated domes with higher rise-to-span ratios are more likely to suffer from progressive collapse [13].

Evidently, there has been substantial research by scholars from different countries on collapse mechanisms of global structures subjected to impact. Existing research mainly focuses on frame structures. However, the existing research on the failure mechanisms of reticulated domes when subjected to impact mostly focuses on the structural field, which is still not fully understood. This paper systematically illustrates finite-element analysis methods for the impact response of reticulated domes. According to the load and structural dynamic responses in various failure modes, the failure mechanisms of reticulated domes subjected to impact are revealed in view of an energy analysis.

2. Finite-element analysis method for impact responses of single-layer Kiewitt-8 reticulated domes based on ANSYS/LSDYNA

2.1. Finite-element analysis method for responses of reticulated domes subjected to impact

Reticulated domes typically have complex structural forms and large spans, whereas an impact load features a strong intensity within a short duration varying rapidly over time. As a result, it is very difficult to study the impact behavior of reticulated domes by only experimental means. Therefore, using numerical simulation methods for this particular research is a promising approach.

2.1.1. Strain rate effect

The strain rate effect refers to the yield strength and instantaneous stress of materials increasing with increasing strain rate under a strong dynamic load. This is the dynamic behavior of materials and belongs to the field of material dynamics [1]. In the analysis of structures made out of strain rate sensible materials, adopting the material constitutive relations, which are irrelevant to the strain rate, may cause large differences between the theoretical analysis and real results. Therefore, material constitutive relations, taking strain rate effects into account, should be established in the analysis. This is of significant importance to the accuracy of numerical study results (e.g., steels are strain rate sensible materials). In ANSYS/LSDYNA, there are the Piecewise Linear and Johnson-Cook material models that consider metal strain rate effects.

The Piecewise Linear model uses the Cowper-Symonds equation to incorporate the strain rate effect, and the relationship between strain rate and yield stress is:

$$\sigma_Y = \left[1 + (\varepsilon'/c)^{\frac{1}{P}}\right](\sigma_0 + f_h(\varepsilon_{eff}^{p}))$$

where σ_0 is the yield stress under constant strain rate, $\dot{\varepsilon}'$ is the effective strain rate, C and P are strain rate parameters, and $f_h(\varepsilon_{eff}^{p})$ is the hardening function based on effective plastic strain [14]. This model is relatively simple and has a wide application in practice; however, it fails to consider the material softening effect under increasing temperatures.

The Johnson-Cook model not only considers the variation of strain rate but also incorporates the softening effect of materials under increasing temperature. Its constitutive relationship and rupture strain can be described by the following two equations:

$$\sigma_e = [A + B(\varepsilon_e^{p})^n](1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m})$$

$$\varepsilon^f = [D_1 + D_2\exp(D_3\sigma^*)](1 + D_4\ln\dot{\varepsilon}^*)(1 + D_5T^*)$$

where A, B, C, n, m, and D_1 to D_5 are parameters with values that are experimentally fitted for different materials [15]. Lin et al. conducted experiments on Q235 steels (commonly used in the Chinese building industry) and the results show that the Johnson-Cook model is different from the Piecewise Linear model under high-speed impact [4]. Though the material model “Johnson-Cook” could takes tempreture into account, the tempreture effect is not obvious when the $v \le 400$ m/s according to the research [15]. When the impact speed stays below 400 m/s, both models provide similar results, yet adopting the Piecewise Linear model can improve the calculating speed.

2.1.2. Propagation of stress waves and dynamic responses of structures

For a short action duration of the load and a large enough object dimension in the loading direction, the disturbance will gradually propagate to previously undisturbed regions when local regions are subjected to impact. This phenomenon, called propagation of stress waves, is mainly used to study the local disturbance in the object and its propagation to the global region, and dynamic responses are studied in the process. For thin-walled structures, such as plates, shells, and beams, when the load is applied in a direction of minimal dimension, the action time of stress waves towards this direction is much shorter compared to the external load. After several cyclic propagation reversals, stress waves in this direction tend to be homogenized, and all the mass points in the direction of the load action will produce global motion. Such motion is called a structural dynamic response, and is reflected by structural deformation and its change over time as well as the final results of the fracture, penetration, or failure of structures [1]. In this study, the propagation of the disturbance is ignored, and research is focused on structural deformation and fracture as well as their relationship with time. Metal materials usually possess very high elastic wave velocities (for steel, this is 5.1 km/s), whereas reticulated domes are subjected to impact in the normal direction, i.e., the direction with the smaller dimension of steel tubes (the diameter of steel tubes is typically smaller than 200 mm). Generally, all the mass points in the normal direction of the structures will be affected within microseconds. Therefore, the propagation of stress waves in steel tubes can be ignored, and the research mainly focuses on the dynamic response of structures, including the stress and strain in members. This belongs to the field of structural dynamics. However, the in-plane geometrical dimension is very large (The span of reticulated dome is dozens of meters.), and attention needs to be paid to the propagation of local disturbance to the global structure resulting from impact in the in-plane direction of reticulated domes, i.e., the in-plane propagation of stress waves can be realized by studying the development of global structural responses [16].

2.1.3. Damping force action

Due to the extremely short duration of impact in the whole process, the impact is finished before the damping force takes action. Consequently, the damping effect is always ignored. However, for global structures like reticulated domes, their natural vibration periods and maximum response duration are much longer than the impact duration, and after the impact load is completed, there is always a relatively long time before maximum dynamic responses occur in structures. Therefore, action from the damping force should not be ignored prior to the occurrence of the maximum responses in the structure, and the effect of damping on structural impact responses should be appropriately taken into account. Otherwise, there may be a large difference

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