Thin-Walled Structures 82 (2014) 24–32

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Experimental and numerical study of circular, stainless thin tube energy absorber under axial impact by a control rod

Zhe Yang [a], He Yan [b], Chenguang Huang [a], Xingzhong Diao [b], Xianqian Wu [a], Shaohua Wang [b], Lingling Lu [a], Lijuan Liao [a], Yanpeng Wei [a,*]

[a] *Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China*
[b] *Institute of Nuclear and New Energy Technology of Tsinghua University, Key Laboratory of Advanced Reactor Engineering and Safety, Ministry of Education, Beijing 100084, China*

ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form
27 March 2014
Accepted 27 March 2014
Available online 25 April 2014

Keywords:
Circular thin tube
Energy absorber
Progressive buckling
Axial impact
Strain rate
Interfacial pressure

ABSTRACT

In this study, several crashworthiness parameters of a circular, thin tube energy-absorbing structure, which is used in a high-temperature, gas-cooled reactor (HTR), are studied experimentally and numerically at various tube thicknesses, temperatures and impact velocities. The average crushing force is fundamentally dependent on strain hardening, strain rate hardening, and, particularly, temperature softening of the material. The peak forces during buckling are significantly affected by the local strain rate in the material and exhibit a decreasing trend in sequentially formed folds. Reducing the tube thickness is an effective method to weaken the average crushing force, but it does not weaken the maximum crushing force. Additionally, the stress concentration at the edge of the backplate–graphite contact surface is evaluated in detail to ensure the structural security of the energy absorber.

1. Introduction

Impact is a critical issue in the design of control systems in nuclear power plants [1,2]. The control rods, which are slender and massive, are inserted into the reactor via a free fall once a shutdown signal is triggered. The free-fall control rod, after travelling through the nuclear reaction zone, will substantially impact the graphite reactor structure [3,4]. This phenomenon is more serious in a high-temperature gas-cooled reactor (HTR) [5,6] because there is no liquid to decelerate the control rod in the nuclear reaction zone. Therefore, an impact energy absorber is required between the control rod and the graphite reactor to weaken the impact force and disperse the impact energy. Furthermore, due to the low strength and brittleness of graphite, which is the main constituent material of the reactor, and the ultra-clean spaces required for a nuclear reaction, the design demands the following:

i. The pressure imposed on the reactor structure during the entire impact event is strictly limited below the maximum allowable stress of graphite at all locations.
ii. The absorber structure must exhibit good stability under extremely high environmental temperatures.
iii. There must be no debris or other additional products during impact energy absorption.

Circular thin tubes, which are the most efficient and reliable energy absorbers, may be an appropriate structure to service in such strict conditions [7–9]. From the perspective of an energy absorption capacity, it has been found that a circular, thin tube under axial compression is one of the best devices because it provides a reasonably high specific energy ($\sim 3\times 10^4$ Nm/kg), high volumetric efficiency (0.7–0.8) and has a simple geometry [10]. More importantly, its progressive buckling behavior can provide approximately a constant crushing force, which is the prime characteristic of the energy absorber for our purposes. At quasi-static conditions, due to the complexity of plastic hinge formation mechanism, the evaluated average crushing force is different for different buckling modes (Concertina, diamond and mixed). Alexander presented a rigid-plastic analysis to theoretically estimate the concertina mode [11], which is the most famous equation for energy absorption criteria in axial crushing of circular tubes. Abramowicz and Jones [12] improved Alexander's analysis, which gave a more consistent agreement with experimental results. Pugsley and Macaulay [13] presented an expression for the

* Corresponding author. Tel.: +86 10 82544256.
E-mail addresses: Huangcg@imech.ac.cn (C. Huang), weiyanpeng@imech.ac.cn (Y. Wei).

http://dx.doi.org/10.1016/j.tws.2014.03.020
0263-8231/

Nomenclature

D	diameter of tube
D_1	diameter of backplate
h	thickness of tube
L	length of tube
H	length of control rod
Φ	diameter of control rod
S	area of backplate
a	length of graphite
Y	yield strength of stainless steel
ρ	density of stainless steel
E	Young's modulus of stainless steel
E_1	Young's modulus of graphite
M	Mass of control rod
m	Mass of backplate
σ_{eq}	von Mises flow stress
ε	equivalent plastic strain
$\dot{\varepsilon}$	equivalent plastic strain rate
$\dot{\varepsilon}_0$	reference strain rate, 1 s^{-1}
$\dot{\varepsilon}_0^*$	dimensionless strain rate
μ	Poisson's ratio
V	impact velocity
E_{in}	input kinetic energy
T	environmental temperature
T_r	room temperature
T_m	melting temperature of stainless steel
T^*	homologous temperature
$F_{\max}$	maximum transient crushing force
F_{av}	average crushing force
$S_{\max}$	maximum crushing displacement
$P_{\max}$	maximum interfacial pressure
P_{av}	average interfacial pressure

average crushing force by assuming that kinetic energy is absorbed by plastic bending and shear of the diamond patterns.

These equations are also suitable a low-velocity impact, where kinetic energy is considered to be converted into plastic work at the quasi-static. In this case, the inertia effect of the structure can be ignored; however, the effect of the loading condition on the mechanical properties of the materials must be considered. Most of the previous work has studied the effect of the average strain rate on the increase in yield stress [14] using the Cowper–Symonds equation [15]. Nevertheless, little work has been done on the effect of temperature. Though, similar to the average crushing force, which is a decisive factor for energy absorption, the transient crushing force is equally important in the design of absorbers because it incurs the maximum load (often occurring at the initiation of the buckling process) that graphite bears. A numbers of works have studied several buckling features and crushing forces of thin tubes subjected to axial impact loads [16,17], including studying the effect of impact velocity, shell geometry, etc. Generally, the profile of the transient crushing force can reflect the non-uniform deformation characteristics of the buckling process, including the initiation, development and termination of the plastic hinges. At an impact condition, these characteristics are manifested as a non-uniform strain rate in the materials. Its effect on the buckling process and crushing force profile has not been fully understood. Another vital factor is the contact pressure at the interface between the absorber and graphite. Due to the higher stiffness of stainless steel, the backplate of the absorber will slightly penetrate into the graphite block during the buckling process, which leads to a non-uniform stress distribution in the backplate–graphite contact region, which requires a detailed understanding of the time and spatial pressure distribution at the absorber–graphite interface.

In this paper, an energy-absorbing structure based on the progressive buckling phenomena of circular, thin tubes is explored to protect graphite from a low-speed impact from a massive control rod. Several crashworthiness parameters, including the average and transient crushing force and interfacial pressures, are studied experimentally and numerically for various impact velocities, temperatures and geometries. The effects of strain rate and temperature on crushing loads characteristics are discussed in detail in the study.

2. Structure of the absorber

As shown in Fig. 1, the energy absorber is composed of a buffer ring, circular, thin tube and a backplate. The inclined surface of the buffer ring is used to weaken the head pressure of the stress wave generated by impact. The backplate is used for the homogenization of the interface pressure between the absorber and graphite. To ensure stability, both ends of the thin tube are inserted into card slots in the buffer ring and backplate. An artificial defect (1 mm width dimple along the entire circumference) is prefabricated at the proximal end of the thin tube to control the start of buckling. The dimensions of the evaluated thin tubes are length $L=450$ mm and diameter $D=80$ mm and various thicknesses (as shown in Table 2).

All the components of the absorber, including the buffer ring, thin tube and backplate, were made of stainless steel with a density $\rho=7930$ kg/m^3, Young's modulus $E=210$ GPa and Poisson's ratio $\mu=0.3$.

3. Experiments

The impact experiments were performed at set conditions ($h=2$ mm, $V=13$ m/s and $T=300$ K). The impact load was generated by a modified control rod, which was made of low-carbon steel with a total length $H=3000$ mm, diameter $\Phi=110$ mm and mass $M=200$ kg. The head of the rod was also machined to an inclined surface to fit the buffer ring. As shown in Fig. 2, the

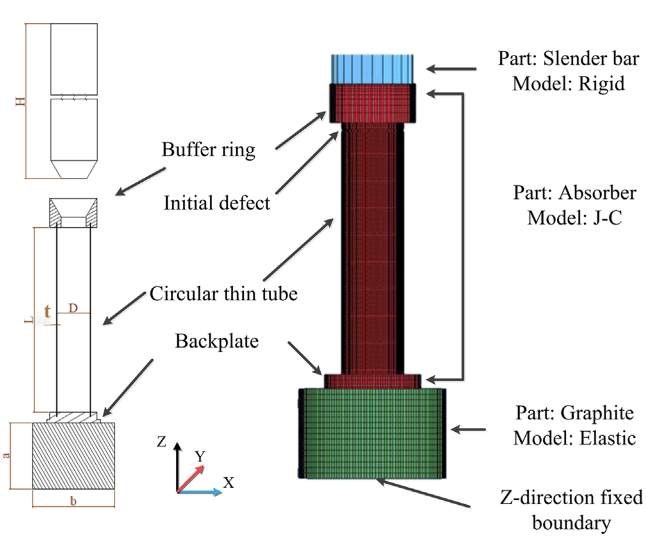

Fig. 1. Schematic structure of the energy absorber and numerical model.