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Numerical analysis of the cracking and failure behaviors of segmental lining structure of an underwater shield tunnel subjected to a derailed high-speed train impact

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A B S T R A C T

Extended finite element analysis was performed to investigate the cracking and failure characteristics of the segmental lining structure of an underwater shield tunnel upon a derailed high-speed train impact, allowing for the optimization of tunnel design under accidental conditions. Dynamic crack analysis of this study focuses on the crack morphology, crack initiation and opening of the concrete segmental lining, along with joint bolts in the circumferential and longitudinal directions. The results showed that impacting the segmental lining structure leads to V-shaped continuous and penetrating cracks in the segment and to continuous long strip or polygonal-shaped cracks in the joint surfaces around the impacting area of the segments as well as their outer surfaces near the joint surface. The major cracks initiate in the center of the impact region, and their maximum openings take place at the impact load peak stage, whereas the cracks in other region mainly occur at the shock stage. All cracks close to different degrees when subjected to subsequent loading. Curved bolt cracks at the longitudinal joint are annular and closed, while those of straight bolts at the circumferential joint are irregularly stripped and closed along the length of the screw. The former may cause screw fracture, while the latter could easily induce peeling of the screw surface layer, consequently decreasing the cross sectional area of the bolt. Increasing train impact speeds may result in an increase in the degree of crack openings occurring at both segmental lining and joint bolts. Interestingly, the cracking damage of the segments and joint bolts at the rear of the impact region seem to be more severe than those occurring at the front with respect to the direction of train travel.

1. Introduction

In recent years, high-speed trains have occasionally derailed around the world, such as the Intercity-Express (ICE) derailing at Eschede, Germany in 1998 (Brabie and Andersson, 2008); KTX high-speed train derailing near Seoul, Korea in 2011 (Koreajoongangdaily, 2011); an express train derailing near Santiago de Compostela, Spain in 2013 (Shultz et al., 2014); among others. Currently, > 16,000 km of high-speed railways (referred to as HSR) are under operation in China. Some of the lines are very complicated, and the potential risks of derailment are a major issue. Meanwhile, the development of shield tunneling introduces new complications. Shield tunnels are commonly used instead of bridges when a high-speed railway needs to run through rivers in China, for example, the Guangzhou-Shenzhen-Hong Kong HSR passes through the Shiziyang River (Feng et al., 2012) and the Hangzhou-Changsha HSR crosses over the Qiantang River (Lin et al., 2013). As the shield tunnel is an assembling of a lining structure connected by prefabricated segments through the bolts at circumferential and longitudinal joints, its integral rigidity is relatively less than that of a tunnel constructed by the mining method. Concrete segments and joints could be easily broken under the impact load, which may lead to the failure of the whole tunnel. Therefore, shield tunnels are more vulnerable to the impact load induced by a high-speed derailing train (Chen and Mo, 2009; Teachavorasinskun and Chub-Uppakarn, 2010). It is important to carry out an anti-impact design for underwater shield tunnels.

This paper studied the dynamic behavior of shield tunnels under an impact load due to train derailment. The cracking damage characteristics of the segments and joint bolts of a shield tunnel are revealed, which could provide guidance for the design of segmental tunnel lining in the future.

The dynamic behavior of structures under impact loads is very complicated. A large number of studies have been carried out, and some achievements have been accomplished by using both experimental tests and numerical simulation. ErayBaran et al. (2007) investigated the behavior of the connections between the girders and floor beams of

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bridges subjected to lateral impact loads. Wu et al. (2015) studied the impact behavior of concrete beams through experimental tests and meso-scale simulations. Zhan et al. (2015) investigated the damage characteristics of a concrete beam under impact and proposed two empirical formulas to estimate the maximum and residual deflection of the beam. Sakdirat and Alex (2010) conducted an experimental test to examine the dynamic crack propagations in pre-stressed concrete sleepers of railway track structures due to severe impact loading. Failure analysis of reinforced concrete walls under impact loads was performed by using the finite element approach (Thai and Kim, 2014). In Ganz's (2011) research, concrete cylinders subjected to impact loads were examined to analyze the kinetic characterization of the process. Different failure modes were also investigated. Amichai and Davide (2014) and Han et al. (2016) analyzed the damage behaviors of tunnel structures under impact from an explosion by numerical simulation. Cui et al. (2015) studied the dynamic responses and damage analyses of the tunnel lining colliding with an errant large vehicle.

By summarizing the current research states, it can be found that: (1) The current research mainly focus on the impact behaviors of concrete components, such as floors, beams and cylinders; (2) to perform an experimental study, drop weight tests and missile impact tests are mainly used. However, the similarity model test of a dynamic system is a less adopted method. (3) Numerical simulations based on the finite element method and discrete element method are commonly used in those studies.

A shield tunnel is an assembly structure system built underground. It is quite different from structures on the ground surface and those built from single engineering components. Train-induced impact loads due to derailment are very complicated. They are affected by many factors, such as the train configuration and impact speed as well as the impact angle (Yan et al., 2016). Therefore, the cracking damage characteristics of the segmental lining structures impacted by a high-speed derailed train need to be studied systematically and step by step. However, very limited research has been found in the literature in this field. Yan et al. (2016) presented a study to determine the train-induced impact load due to derailment, and they also analyzed the dynamic response of a shield tunnel.

On the basis of Yan's previous research results, this paper modelled the cracking and failure behaviors of a shield tunnel lining subjected to impact loads from train derailment at different speeds. Numerical simulation was performed by the nonlinear finite element analysis software ABAQUS. The innovations of this study are as follows: (1) dynamic analysis of the impact load was used in the whole structure of shield tunnels rather than a single concrete component; (2) the joint bolts and joint interface of the segmental tunnel lining are modelled in the numerical simulation, and the numerical model could therefore more accurately simulate the shield lining behavior; and (3) the characteristics of the crack distribution and crack propagation for both the concrete segments and joint bolts were analyzed. By performing this study, the area of the crack distribution, shape of the crack and time history of the crack development at different impact speeds are obtained.

2. Structural crack analysis theory and dynamic solutions

To simulate the crack behavior of concrete, the traditional finite element method can be classified into two categories: the discrete crack model and smeared crack model. Both models are mesh dependent (Moës et al., 1999). This mesh dependence feature restricts the application of simulating crack behavior by using the traditional finite element method. Belytschko and Black (1999) proposed the extended finite element method (XFEM) to solve discontinuity problems within the framework of the conventional finite element method. This XFEM could effectively avoid the mesh dependence problem and is currently widely used (Wells and Sluys, 2001; Moës and Belytschko, 2002; Xu and Yuan, 2009).

In the nonlinear FE software ABAQUS, the crack initiation and propagation process of segment and joint bolt upon impact loads can be simulated by XFEM by introducing the discontinuous displacement model into traditional FE analysis. The discontinuous displacement field is no longer dependent on remeshing, while simultaneously increasing the computational efficiency. XFEM approximation is based on the partition of unity method. The concept is that any function can be expressed by a set of local functions within the domain. Thus, the approximate displacement solution can be stated as

$$u^h(x) = \sum_{i=1}^{N} N_i(x)(u_i + a_i\Phi_i(x)), \tag{1}$$

where$N_i(x)$ is the interpolating shape function; u_i is the displacement of the i-th node; a_i is the corresponding additional degrees of freedom (dof); $\Phi_i(x)$ is the enrichment of the i-th node, reflecting the discontinuous characters of structure; and N is the node set of all elements. For any point, x, within the domain,

$$\sum_i N_i(x) = 1. \tag{2}$$

If the progressive function reflecting the crack surface and progressive displacement field function of the crack tip are regarded as the enrichment function, then the displacement mode can be expressed as

$$u(x) = \sum_{i\in N} N_i(x)u_i + \sum_{j\in N^{dts}} N_j(x)H(x)a_j + \sum_{k\in N^{asy}} N_K(x)\sum_{\alpha=1}^{4}\Phi_\alpha(x)b_k^a, \tag{3}$$

where N^{dts} is the node set of elements thoroughly penetrated by cracks; N^{asy} is the node set with crack tip elements; $N_i(x)$, $N_j(x)$, and $N_K(x)$ are the shape functions of the corresponding nodes; u_i is the continuous part of the nodal displacement vector; a_j is the improved dof of the j-th node related to the Heaviside (strong discontinuity) function; b_k^a is the improved dof of the k-th node related to the elastic progressive crack tip function; $H(x)$ is the improved function; and $\Phi_\alpha(x)$ is the progressive displacement field function of crack tip, reflecting the singularity of crack tip stress.

The Hilber-Hughes-Taylor (HHT) time integration scheme, derived from the basic Newmark time integration scheme (Han et al., 1977), was used for the dynamic analysis. The HHT implicit scheme is highly effective to solve the problem of nonlinear crack development in segmental lining structures (Burlayenko and Sadowski, 2014). The relevant balance, displacement and speed are

$$[M]\{\ddot{u}\}_{t+\Delta t} + (1+\alpha)\{[C]\{\dot{u}\} + [K]\{u\} - P\}_t - \alpha\{[C]\{\dot{u}\} + [K]\{u\} - [P]\}_{t+\Delta t} = 0 \tag{4}$$

$$\{u\}_{t+\Delta t} = \{u\}_t + \Delta t\{\dot{u}\}_t + \Delta t^2\left[\left(\frac{1}{2} - \beta\right)\{\ddot{u}\}_t + \beta\{\ddot{u}\}_{t+\Delta t}\right], \tag{5}$$

and

$$\{\dot{u}\}_{t+\Delta t} = \{\dot{u}\}_t + \Delta t[(1-\gamma)\{\ddot{u}\}_t + \gamma\{\ddot{u}\}_{t+\Delta t}], \tag{6}$$

where$[M]$, $[C]$, $[K]$, and $[P]$ are the matrices for the mass, damping, stiffness and train impact load, respectively; $\{u\}_t$, $\{\dot{u}\}_t$, and $\{\ddot{u}\}_t$are the displacement, speed, and acceleration of the system, respectively; β and γ are decided by the weight factor, α, such that

$$\beta = \frac{1}{4}(1-\alpha)^2, \gamma = \frac{1}{2} - \alpha, \tag{7}$$

and the weight factor α may be arbitrarily assigned over the range $-1/3$-0. When $\alpha = 0$, the H.H.T time integration scheme can be simplified to average acceleration.

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