Tunnelling and Underground Space Technology 69 (2017) 37–51

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Experimental investigation of initial deployment of inflatable structures for sealing of rail tunnels

Eduardo M. Sosa*, Gregory J. Thompson, Ever J. Barbero

Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV 26506-6106, USA

ARTICLE INFO

Keywords:
Confined inflatable
Conformity
Contact
Deployment
Folding
Membrane
Tunnel

ABSTRACT

Large-scale inflatable structures have become a viable alternative for sealing segments of large-diameter conduits or rail transit tunnel sections for preventing propagation of flooding, noxious gasses or smoke. In such applications, the inflatable structure is prepared for placement, either permanently or temporally, and maintained ready for deployment, inflation, and pressurization when needed. The sealing effectiveness depends on the ability of the inflatable structure to self-deploy and fit, without human intervention, to the intricacies of the perimeter of the conduit being sealed. This work presents results of experimental work performed for the evaluation of initial deployment and inflation of a prototype inflatable structure installed in a rail transit tunnel segment for containment of flooding. Folding and packing procedures necessary to prepare and install a full-scale inflatable in the tunnel segment are described. Methods for evaluation of conformity and degree of contact of the membrane with the tunnel section are implemented as well. Test results indicate that a successful distribution of the membrane material over the tunnel perimeter is achieved by a combination of gradual unrolling and controlled membrane release. The membrane distribution during the initial unfolding and inflation, the shape of transitions at corners and angles in the tunnel perimeter; the oversizing of membrane material in the hoop perimeter of the inflatable, as well as the surface texture of the membrane, were identified as main factors that affect the level of conformity and degree contact between the inflatable structure and the tunnel perimeter.

1. Introduction

The protection of underground civil infrastructure is a high priority for transportation and security agencies. In particular, rail transit tunnels running under bodies of water are susceptible to disruptions due to flooding originated by extreme climatic events such as hurricanes, fires or other human-made events (Federal Highway Administration, 2003; TCRP, 2006; Rabkin, 2007; Brezhnev et al., 2005). Some examples of such incidents in the United States include the 1992 Chicago freight tunnel flood (Inouye and Jacobazzi, 1992) which forced the shutdown of the subway system, caused damage to numerous businesses and required the evacuation of about 250,000 people from the area. In 2003, Hurricane Isabel caused flooding of the Midtown Tunnel in Virginia. During this event, about 167,000 m^3 of water from the Elizabeth River flooded the tunnel system in just 40 min. The flooding left the tunnel damaged and closed for nearly a month (Post et al., 2005). Most recently, in New York City, seven subway tunnels under the East River as well as three road tunnels flooded during Hurricane Sandy and remained inoperable for several days (NYC Office of the Mayor, 2013 and Zimmerman, 2014). These incidents and others summarized in Leitner (2001), Kirkland (2002), Haack (2002) and TCRP (2006) have demonstrated a need for research on ways to mitigate vulnerabilities or, at least, minimize the consequences of catastrophic events. Although it is impossible to prevent all situations that can lead to flooding, damage can be substantially minimized by reducing the area affected by the event. To minimize the effects of any eventual threat, a possible approach is to compartmentalize the tunnel system (Tan, 2002). However, it can be difficult, if not impossible, to install or repair in an existing tunnel all the elements required for compartmentalization. Typically, space constraints inhibit the installation of new protective devices such as flood gates. The elevated cost of interrupting the tunnel operations or making major infrastructure modifications have also discouraged attempts to improve the tunnel resilience by these means.

In the recent years, alternative solutions have been proposed to seal tunnel segments susceptible to the consequences of extreme events. In particular, large inflatable structures for protection of civil transportation infrastructures, such as railway tunnels, large pipes or mines, have been under development in the recent years as reported by Barrie (2008), Martinez et al. (2012), Fountain (2012), Lindstrand Technologies (2013) and Stocking (2013). Large scale inflatable dams

* Corresponding author.
E-mail addresses: eduardo.sosa@mail.wvu.edu (E.M. Sosa), gregory.thompson@mail.wvu.edu (G.J. Thompson), drb@wvu.edu (E.J. Barbero).

http://dx.doi.org/10.1016/j.tust.2017.06.001
Received 18 December 2016; Accepted 2 June 2017

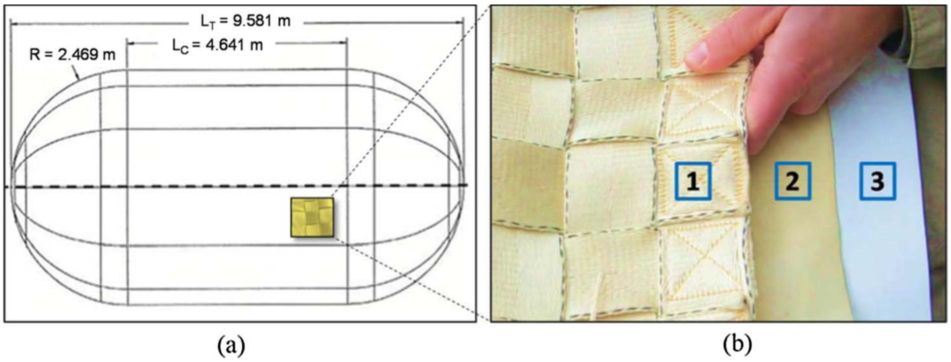

Fig. 1. Inflatable Plug: (a) Dimensions for unconstrained inflation; (b) Membrane architecture: [1] External macro fabric comprised of woven webbings; [2] Intermediate protective fabric; [3] Internal bladder.

for flooding control have also been studied by Carter et al. (2001), Ghavanloo and Daneshmand (2010) and Sklerov and Padilla (2012).

The implementation of large-scale inflatable structures (also called inflatable plugs) inside transportation tunnels intends to prevent or reduce the damage induced by hazardous events by creating a compartment to contain the threat (Tan, 2002). Potential threats include flooding, smoke or noxious gasses that can propagate through a tunnel system and compromise its functionality and structural integrity. The idea is that one or more inflatable structures are installed at specific locations of the tunnel to create a compartment that can isolate the compromised region (Tan, 2002; Martinez et al., 2012). Recently, Barbero et al. (2013a,b) and Sosa et al. (2014a–c) reported testing efforts to demonstrate the feasibility of containing flooding with large inflatable structures. Under these efforts, multiple tests were performed at different scales using specially built testing facilities designed to simulate flooding of a tunnel segment.

The implementation of inflatable structures for sealing of rail transit tunnel segments can be divided into three main phases: I-Preparation and installation of the inflatable; II-Deployment; and III-Pressurization.

Phase I requires the definition and implementation of a folding sequence in conjunction with the packing of the folded plug in a storage container. This phase also includes the transportation and installation of the folded plug at specific locations inside the tunnel segment to be sealed, leaving it ready to be activated when needed.

Phase II begins with automatic opening of the storage container, which allows the liberation of the inflatable followed by inflation until it reaches its final shape and position within the tunnel section. The deployment and initial inflation of the plug are performed using air at relatively high flow rates, typically in the range of 25–50 m^3/min, to allow rapid expansion and positioning of the inflatable which can be achieved in the range of 2–5 min. With these air flow rate levels, the internal pressure of the plug is relatively low, in the range of 2–7 kPag (Barbero et al., 2013b; Sosa et al., 2014a).

Phase III begins immediately after the initial positioning achieved by high-flow and low-pressure inflation implemented in Phase II is complete. In Phase III, the plug is pressurized so it can withstand, predominantly by friction, the external pressure originated by flooding. The magnitude of the pressurization depends on the level of flooding pressure expected to be contained. For example, in the full-scale tests performed by Barbero et al. (2013b) and Sosa et al. (2014a), the inflatable plug was pressurized up to 117 kPag and then subject to water flooding at a pressure of 80 kPa. These tests demonstrated that the sealing capacity of the pressurized inflatable is highly influenced by the level of local and global conformity achieved during Phase II, which in turn depends on how the inflatable was prepared in Phase I (Barbero et al., 2013b; Sosa et al., 2014a).

With the previous considerations, the work presented here is completely focused on the analysis and understanding the results of experimental evaluations corresponding to Phases I and II delineated previously. Folding and packing procedures that can be implemented in a full-scale inflatable along with the need for implementation of passive mechanisms for controlled release of the membrane are described in detail. Experimental results of initial deployment and inflation tests are presented and discussed for the purpose of identifying key aspects of the deployment dynamics that influence the sealing capacity of the inflatable plug once it is fully positioned in the tunnel. Methods developed for evaluating conformity, and the results of their implementation in the experimental evaluations are described in detail as well.

The outline of this paper is as follows: an overview of the characteristics of the full-scale prototype inflatable plug used for the tests are presented first. Folding and packing procedures are described next, followed by an overview of the full-scale test setup and the two methods developed for evaluation of conformity. Test results and discussions followed by a summary of significant observations, considerations for implementation and conclusions are presented at the end.

2. Inflatable plug

The full-scale prototype inflatable plug manufactured for the test presented here consists of a cylindrical segment closed by two hemispherical end caps. The cylindrical segment has a diameter of D_c = 4.940 m and a length L_c = 4.641 m. The radius of each hemispherical end cap is R = 2.469 m, and the total length of the plug is L_T = 9.581 m (Fig. 1a). The design, including the shape and dimensions, is based on the procedures proposed by Barbero et al. (2013a) and Sosa et al. (2014c). The design is based on the premise that the stability of the plug is achieved by providing sufficient frictional force to counteract an external force such as a flooding pressure. The frictional forces are generated by the contact between the membrane of the cylindrical segment of the inflatable and the surrounding inner perimeter of the tunnel section where the plug is deployed and pressurized. The length of the cylindrical segment is determined based on friction tests run at the coupon level on samples of membrane materials and validated by reduced-scale prototypes subjected to induced slippage under wet conditions (Sosa et al. (2014b)). The same prototype was used for full-scale flooding simulations to demonstrate the ability of the inflatable to remain in equilibrium while containing the flooding pressure with manageable leakage rates as described in Barbero et al. (2013b) and Sosa et al. (2014a).

The perimeter of the cylindrical portion was designed to cover elements that typically exist in a tunnel segment, such as duct banks, pipes, cables, and rails. Typically, the design of the perimeter of the cylindrical portion of the plug accounts for all the elements present in the tunnel that should be covered by the membrane. In an ideal design, the oversizing of the membrane would be no more than 1% to 2% of the nominal perimeter to cover, and this percentage of oversizing is accounted as part of the manufacturing tolerance. However, preliminary tests performed using a surrogate inflatable plug demonstrated that the deployment and distribution of the membrane are not uniform. These preliminary results demonstrated a tendency of portions of the membrane to create local bridging close to corners, transitions or around