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Finite element simulation of deployment of large-scale confined inflatable structures

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ABSTRACT

Large-scale inflatable structures have become a viable alternative for sealing and isolating segments of large-diameter conduits or tunnel sections to prevent the propagation of flooding, noxious gases or smoke. In such applications, the inflatable structure is prepared for placement, either permanently or temporary, and left ready for deployment, inflation, and pressurization when needed. Once deployed and in operation, the level of sealing effectiveness depends on the ability of the inflatable structure to deploy and self-accommodate, without human intervention, to the intricacies of the perimeter of the conduit being sealed. This work presents finite element evaluations of the deployment and inflation of a full-scale inflatable plug placed within a tunnel section. Folding sequences and controlled deployment techniques developed experimentally served as the basis for the development of finite element models that can simulate different stages of folding, placement, initial deployment and full inflation of the structure. The good level of correlation between experimental and simulation results in terms of deployment dynamics, levels of contact as well as number and position of zones with no contact in the confining perimeter, demonstrate that the proposed modeling strategy can be used as a predicting tool of the behavior of a large-scale inflatable structure for a given confining environment.

1. Introduction

The protection of underwater and underground assets is of a high priority for transportation and security agencies around the globe. Underwater rail transit tunnels are susceptible to disruptions due to flooding originated by extreme climatic events such as hurricanes or man-made events [1–3]. Some examples of such incidents in the United States include the 1992 Chicago freight tunnel flood 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 [4]. 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 [5]. 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 [6,7]. These incidents and others summarized in [2] 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 threatening event. In order to minimize the effects of any eventual threat, a possible approach is to compartmentalize the tunnel system. 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. One type of thin-walled structures are the inflatable structures [8]. In particular, large-scale inflatable structures for protection of civil transportation infrastructure, such as railway tunnels, large pipes or mines, have been under development as reported by Barrie [9], Martinez et al. [10], Fountain [11], Lindstrand [12] and Stocking [13]. The implementation of large-scale inflatable structures (also called inflatable plugs) inside

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transportation tunnels is intended to prevent or reduce the damage induced by hazardous events by creating a compartment to contain the threat. Potential threats include flooding, smoke or noxious gases that can propagate through a tunnel system and compromise its functionality and structural integrity. The inflatable structures can be installed at specific locations of the tunnel in order to create a compartment that can isolate the compromised region [10]. Most recently, Barbero et al. [14,15] and Sosa et al. [16,17] reported testing efforts performed at different scales to demonstrate the feasibility of containing flooding with inflatable structures. Under these efforts, multiple tests were performed using specially built testing facilities designed to simulate flooding of a tunnel segment. These tests generated valuable experimental information and provided several lessons for field implementation. However, carrying out this type of tests, especially at the full-scale level, is a complex task in which only a limited number of evaluations can be completed within the limits of the allocated time and resources.

The implementation of large-scale inflatable structures for sealing tunnel segments can be divided into three main phases: I. Preparation and installation of the inflatable; II. Initial deployment and inflation; and III. Pressurization. Phase I requires the definition and implementation of a folding pattern in conjunction with 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 system, leaving it ready to be activated when needed. Phase II begins with the detection of a threatening event, which triggers automatic opening of the storage container allowing the liberation of the inflatable followed by inflation until it reaches its final shape and position for isolating specific tunnel segments. When the plug is fully inflated and in place, Phase III starts with the pressurization process for maintaining the plug in position, predominantly by friction, while it withstands the external pressure originated by flooding or gases [10,14–17].

Full-scale tests corresponding to Phase III showed that the sealing capacity of the pressurized inflatable is a function of the level of local and global conformity achieved during Phase II. Moreover, full-scale tests of Phases I and II demonstrated that it can take several iterations to achieve satisfactory results that cannot be predicted in advance [15,16]. Consequently, the development of simulation models based on finite element analysis became imperative to have a predicting tool that can anticipate the performance of the inflatable during the different phases of implementation and operation. As such, this work focuses on the simulation work developed for Phases I and II outlined previously.

An overview of full-scale experimental work that served as a reference for the development of finite element (FE) is presented first, including key features that were implemented later in the development of the FE simulations. The modeling approach and a description of relevant components of the FE models are introduced next, followed by simulation results and comparison of the level of correlation with experimental results. Significant observations and conclusions are presented at the end.

2. Overview of experimental investigation

2.1. Inflatable plug

The full-scale prototype manufactured for testing purposes consists of a cylindrical segment closed by two hemispherical end caps. The design of the inflatable plug for sealing a tunnel section is based on the procedure outlined by Barbero et al. [14]. The cylinder has a diameter of 4.940 m and a length of 4.641 m. The radius of each hemispherical end cap is 2.469 m, and the total plug length is 9.581 m. The length of the cylindrical segment was determined based on friction tests run at the coupon level on samples of membrane materials and validated by small-scale prototypes subjected to induced slippage [17]. 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. However, a manufacturing oversizing of 5% was added to the nominal perimeter to ensure maximum contact of the plug membrane with the tunnel perimeter. The length of the cylindrical portion of the plug provides sufficient contact length for the development of frictional forces to maintain the axial stability, while the circumferential perimeter of the cylinder ensures local conformity of the plug to the tunnel inner perimeter.

The membrane of the inflatable plug consists of a three-layer system comprised of an internal bladder, an intermediate protective fabric, and an external macro-fabric. The bladder is the innermost layer of the construction and is in direct contact with the fluid used for inflation and pressurization. The function of the intermediate fabric restraint is to protect the inner bladder. The outermost layer is a macro-fabric comprised of woven webbings following a plain weave pattern. The webbings of the macro-fabric are 5-cm wide, 3-mm thick and are manufactured with Vectran fibers [18]. Structurally, the outermost layer is the most important since it carries the membrane stresses generated by the pressurization while the two inner layers provide water tightness and contribute to the total mass and volume of the membrane. Two metallic fittings for inflation and air-release are also integrated into the membrane of one of the hemispherical end caps. The total weight of the inflatable plug including inflation fittings is approximately 907 kg. An overview of the inflatable plug during an unconfined inflation is illustrated in Fig. 1(a).

2.2. Folding and packing

In aerospace applications, inflatables are typically folded following two main patterns. One of the simplest folding patterns is the "z-fold" in which the inflatable is flattened before being simply folded back and forth at regularly spaced intervals at discrete lines or hinges. However, despite the simplicity, the discrete nature of the folding creates a discontinuous structure that, during the inflation, restricts the airflow between sections and results in a structure that is sensitive to small changes in shape with an unpredictable and dynamically unstable deployment path [19,20]. The other common folding pattern is by rolling or coiling the deflated structure. This is an effective and compact method to fold and pack an inflatable structure with minimal residual creases. Depending on the configuration, rolling can be in a single or multiple directions. For this folding method it is common to implement passive controls or retardation devices, such as coil springs, Velcro strips or tie-downs installed to produce a more predictable deployment by controlling the final unrolling velocity and minimizing sudden release of sections. This technique results in a more controlled deployment that tends to be much more stable dynamically [19].

In this work, a combination of folding by rolling and installation of passive controls was implemented experimentally and later reproduced in the FE simulations. A sequence of preparation steps was developed for packing the deflated plug inside a portable container that was later placed inside a mockup tunnel section specially built for full-scale tests. These steps were designed to systematize the preparation process so it can be repeated consistently and for maximizing the contact between the membrane and elements installed on the perimeter of tunnel inner perimeter. The maximization of contact was achieved by minimizing the formation of gaps in sensitive areas such as corners and changes of direction in the profile that will later reduce the sealing