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INFLATABLE PLUG FOR THREAT MITIGATION IN TRANSPORTATION TUNNELS

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ABSTRACT

Tunnel safety has long been a concern for transportation and government entities. Fires, noxious fumes, deadly gasses, and flooding threats have occurred in major transportation systems from Madrid to Chicago to Tokyo. The current paper presents the Resilient Tunnel System (RTS). This is a passive protection system developed to mitigate the effects of a hazardous event in the tunnel and the connected infrastructure, by compartmentalizing it. This is achieved by adapting an existing concept: an airbag. The RTS consists of inflating at least two large airbags inside the tunnel, within a specific strategic location, to seal the compromised tunnel section. The seal provided by the airbags must be tight and conform to the tunnel geometry, so whatever occurs between the airbags does not affect the external sections of the tunnel. This paper describes the first prototype of the RTS developed, as well as the tests performed to validate its performance.

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1. INTRODUCTION

Tunnel safety is a subject of special concern, not only because tunnels are of difficult and limited accessibility, but also because most of the potential threats, such as fires, flooding, or noxious substances not only compromise the integrity of the section where the event takes place, but also the entire connecting system, as the threat can spread along it. A good example is the Great Chicago Flood of 1992 [1] in which an initial leak, which could have been repaired easily if it had been done in time, flooded the complete tunnel freight system in downtown Chicago. The freight tunnels have a cross section of 2.8 x 1.3 m and at the time of the accident they represented a network of more than 80 km (50 miles) that was used to run through TV, telephone, and power conduits. The flooding of the buildings connected to these tunnels, as well as possible damage produced by the flooding to the structure of the buildings, forced more than 250,000 people to evacuate. Pumping water from the tunnel system took five and a half weeks at a cost of $40 million [2].

Although it is difficult to prevent all situations that can lead to initial flooding, or any other kind of threatening event, damage can be substantially minimized by reducing the region affected by the event. In the Great Chicago Flood, if the water flow had been stopped when it was first noticed, it would probably have not been necessary to evacuate Chicago's downtown, and the removal of any flooding water from the tunnel could have been accomplished using the existing tunnel draining system. To minimize the effects of any eventual threat, a possible approach is to compartmentalize the tunnel system. However it is difficult, if not impossible, to install in an existing tunnel the elements required for compartmentalizing it. Usually there is no space available for installing conventional protective devices and the cost of interrupting the tunnel operations to proceed with the required construction works underscores any attempt to improve the tunnel resilience by these means.

With this scenario, the present paper proposes a new solution for threat mitigation in transportation tunnels: the RTS. This consists of inflating one or more large airbags inside the tunnel, within a specific strategic location, to seal the tunnel section in case of a threatening event. The airbags must conform perfectly to the tunnel geometry and the seal provided must be tight enough so whatever occurs on one side of an airbag or between adjacent airbags does not affect the external sections of the tunnel. A schematic representation of the approach proposed with the RTS is illustrated in figure 1, which shows the deployment sequence of two adjacent airbags.

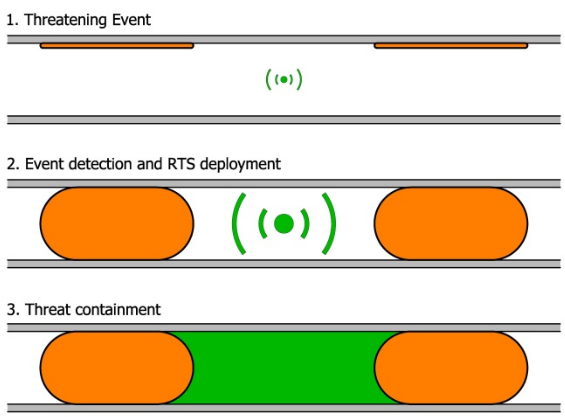

Figure 1: Resilient Tunnel Concept deployment sequence for a threat event

Using an inflatable structure to seal the tunnel provides various advantages compared to other sealing systems; among them are:

- The limited space required by the packed airbag and its low weight makes the RTS easy to adapt to any tunnel without requiring major modifications of the tunnel geometry.
- The simple and fast installation of the RTS can avoid costly traffic interruptions of the transit system, as well as other associated problems for the transit authorities and users.
- The two advantages described above, together with the expected relatively low cost of the solution proposed (compared to other sealing systems) makes it possible to install the RTS at multiple locations, increasing the protected areas of the infrastructure.

Using inflatable structures for protection has been already applied to other fields such as automobile airbags, or the airbags used for the Mars pathfinder [3]. However, tunnel protection using an inflatable structure brings new challenges, due to the large scale of the problem and the complex geometry to which the inflatable has to conform.

The stresses in inflatable structures are proportional to the radii of curvature in the inflatable, at locations where stresses are computed, and to the inflation pressure [4]. In the case of transportation tunnels, where the cross section can have diameters between 4.5 and 6 m, the scale of the problem is an important factor as it requires high fabric strengths. An inflatable structure with such demanding characteristics would be unthinkable if not for the latest improvements in fabrics technology. In recent years, fabrics have increased their strength and long term performance by incorporating new fibrous materials, such as aramids or liquid crystal polymers, and also by the improvement on the polymers used to coat the fabric, such as urethanes and silicones. It is also worth noting the improvements made on fabric-welding techniques, which are now capable to nearly match the fabric tensile strength. The advances on fabric technologies have been complemented with the improvements made on the computational techniques of inflatable structures [5]. Due to these new advances, it is now possible to simulate inflatable structures with complex geometries and/or demanding structural performances.

This paper presents a first attempt to mitigate threats in transportation tunnels by compartmentalizing them with an inflatable structure. The RTS is capable of sealing tunnels to contain low pressure flows, such as gases or non-pressurized fluids. The system described also sets the basis for more demanding applications, such as having to contain flooding in a tunnel. The following section provides a detailed description of the RTS developed. Then, the paper describes the test used to validate the correct performance of the system and the conclusions obtained from this test. The last section presents a discussion of the different results obtained.

2. DESCRIPTION OF THE RESILIENT TUNNEL SYSTEM

The RTS consists of one or more plugs, or inflatable structures, that can seal the tunnel in specific strategic locations. To accomplish this task, the RTS requires several components, among them: inflatable plugs capable of sealing specific tunnel sections, an inflation system that can deliver the fluid used for inflation, and a sensing system that can detect a threat and initiate the deployment of the inflatable. The sensing system can present large variations in its configuration depending on the threat to be detected, and the requirements of the transportation tunnel where the RTS is installed; these concerns are beyond the scope of the present paper. This paper focuses on the inflatable structure and the inflation mechanism, and on the capacity of this concept to seal a specific tunnel section.

2.1 Inflatable Structure

2.1.1 Geometry

The inflatable developed for the RTS consists of a cylindrical region closed by two spherical end caps. A schematic representation of this geometry is shown in figure 1. The cylindrical region is the one in contact with the tunnel inner walls and, therefore, it is the region of the inflatable responsible for sealing the tunnel. The cylinder is closed by two spherical end caps, as this is the most efficient geometry to close the cylinder, minimizing the stresses in the fabric material. The geometry just described corresponds to a plug designed to seal an ideal circular tunnel. However, mass transportation tunnels are often not perfectly circular and they usually contain multiple elements in them such as water pipes, power, and telecommunication conduits, etc. Figure 2 shows a common cross section of a rail tunnel. In this case, the basic plug geometry defined by a cylinder and two spherical end caps has to be adjusted to the more complex tunnel cross section.

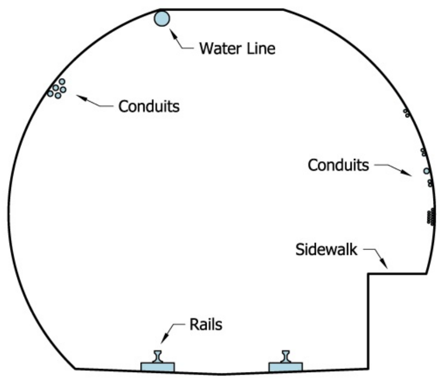

Figure 2: Cross section of a common railway tunnel

The diameter of the cylinder, for a plug capable of sealing the tunnel cross section shown in figure 2, has to be defined based on the total perimeter to which it has to conform. Therefore, it is necessary to take into account the different protruding elements existing in the cross section. Small elements are taken into account just by increasing the cylinder's diameter. On the other hand, large elements, such as the sidewalk, must be taken into account by defining an indentation in the inflatable geometry. Following this approach, the cylindrical region of the inflatable defined for the tunnel cross section shown in figure 2 is conceptually shown in figure 3a. The plug of figure 3a is expected to conform to the tunnel as is shown in figure 3b.

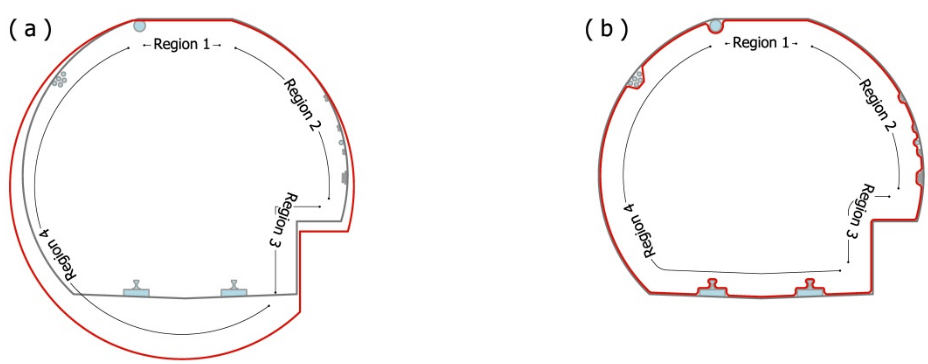

Figure 3: (a) Inflatable plug required for a real tunnel cross section and (b) plug conforming to the tunnel cross section

To have a good seal of the tunnel, the regions one to four shown in figure 3a must be slightly larger than the actual regions of figure 3b. Having a larger perimeter ensures that the inflatable will be able to conform to any protrusion not considered during the design, and that there will be enough fabric to conform to the tunnel section, even if the inflation is not perfectly adapted to the tunnel geometry and some protrusions are not placed exactly where they should be (e.g., wrinkles in one rail can use more fabric than was expected). On the other hand, the perimeter of the different regions cannot be much larger than the required length because an excess of fabric can generate too many wrinkles, and each wrinkle is a possible leak path when the inflatable is in use.

2.1.2 Inflation pressure and structural performance

The sealing capacity of the inflatable structure not only depends on the plug geometry but also on the pressure at which it is inflated. To seal a tunnel section, the inflation pressure in the inflatable must be larger than the external pressure. The external pressure is determined by the fluid to be contained. In the case of a gas or fire (in this last case, the idea is to deplete the available oxygen within the sealed area), the fluid pressure is the atmospheric pressure. Otherwise, if the thread to be contained is a liquid, the external pressure corresponds to the value at which this liquid is pressurized; for example, the head of water in an underwater tunnel section flooded because of a leak.

There are two main reasons why the inflation pressure has to be larger than the external pressure. The first one is functional: if the fluid to be contained exerts a higher pressure than the inflatable, the fluid will infiltrate the interface between the plug and the tunnel walls, creating leakage areas that will make it difficult for the plug to seal the tunnel. The second reason is structural: if the external pressure is larger than the inflation pressure, the inflatable will change its assumed geometry and, consequently, its load distribution. The new configuration, if it has not been considered in the calculation, can lead to structural failure of the device.

Once the inflation pressure and the geometry of the inflatable are defined, the expected fabric stresses for the RTS can be calculated to define the fabric strength required. A simplified estimation of the fabric stresses can be obtained by dividing the inflatable geometry in two regions: the cylindrical part, in contact with the tunnel surface, and the end caps. Stresses in the cylindrical part are rather small, as the internal pressure is transferred directly to the tunnel walls. On the other hand, membrane stresses at the end caps are directly related to the applied internal pressure and the radius of curvature of the spherical end cap. The membrane stress of the end cap is:

$$\sigma_{sph} = pR/2 \qquad [1]$$

Where p is the difference between the inflation pressure and the external pressure, and is the radius of the sphere.

2.1.3 Axial stability

The RTS not only has to seal the tunnel, but also has to be axially locked in the tunnel section where it is installed. This is not a major problem if the RTS is used to contain gases. But, if the RTS is used to contain floods, the axial load exerted by the head of water over the plug can be high enough to induce axial displacement of the RTS, which becomes an important consideration in the design process.

To axially lock the inflatable structure in the tunnel, there are two possible methods: using a mechanical anchorage of the inflatable to the tunnel section or relying on friction between the inflatable plug and the tunnel walls. Of these two alternatives, the preferred method is based on friction between the plug and the tunnel, as it distributes the load along the tunnel perimeter, and is therefore less harmful to the tunnel and the inflatable plug, as opposed to having concentrated loads at the anchorage region. So, using friction to axially lock the plug into the tunnel, the external axial forces acting on the system, with resultant F_{ext}, must be lower than the friction forces, with resultant F_{frc}:

$$F_{ext} \leq F_{frc} \qquad [2]$$

The friction forces depend on the friction coefficient between the fabric and the tunnel inner walls, μ; the normal pressure exerted by the fabric over the tunnel surface, in this case, the inflation pressure P_{int}; and the contact surface area S_c. Therefore,

$$F_{frc} = \mu \cdot P_{\text{int}} \cdot S_c \qquad [3]$$

The friction coefficient is defined by the surface characteristic of the tunnel and the fabric used for the RTS; and the inflation pressure is defined by the requirements of the external pressure to be contained. In general to satisfy equation (2), the main parameter to be defined is the contact surface area, which depends on the perimeter of the tunnel cross section (fixed value) and the length of the cylindrical portion of the inflatable. Therefore, the length of the plug can be defined by the resultant friction force required to axially lock the RTS within the tunnel section, including any desired safety factor.

2.2 Deployment and Inflation System

The deployment and inflation of the RTS must be accomplished within a relatively short time, to seal the tunnel section before the potential threatening event causes damage to further sections of the tunnel system. The mechanism used must also allow for a correct positioning of the plug within the cross section, so it can conform to all existing protrusions and provide a good seal of the tunnel cross section. The correct position of the inflatable structure in the tunnel is achieved by using a sequential deployment procedure. This consists of restraining sections of the structure during the inflation process, preventing the full deployment of such sections until a defined internal pressure has been reached within the inflatable. When such limiting pressure has been reached, the restraint is released and the constrained sections of the plug are deployed and inflated, to conform to their designed geometry.

For the tunnel section considered (figures 2 and 3), this procedure is used to correctly accommodate the indentation made in the plug over the sidewalk, as shown in figure 4. The deployment of the inflatable structure takes place typically from the top of the tunnel. The restraint used consists of a set of nylon lines distributed along the plug length. These lines maintain the indentation over the sidewalk when the plug is deployed (figure 4a). When the plug is partially inflated, the tension forces in the nylon lines reach their strength capacity and they break (figure 4b), allowing the indentation in the plug to move into its correct position. With this procedure the inflatable structure is thus capable of sealing the tunnel cross section (figure 4c).

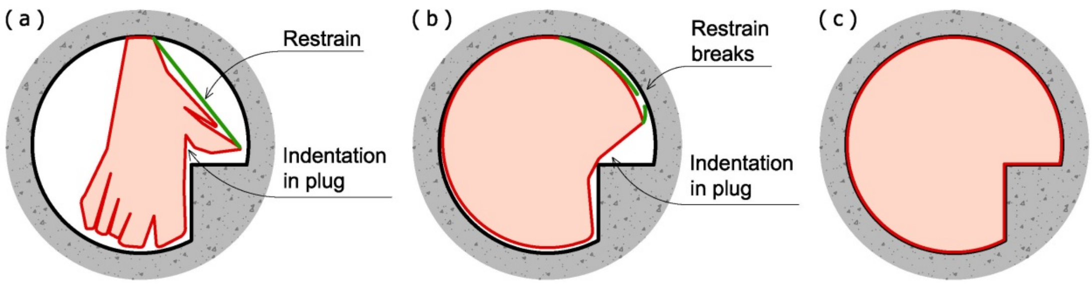

Figure 4: Sequential deployment procedure used to accommodate the sidewalk

The fluid used to inflate the RTS depends on the threat to be contained. If the RTS has to stop the flow of gases in the tunnel system, the plug does not require a high inflation pressure. In this case, pressures between 0.05 and 0.1 atm are sufficient to seal the tunnel. This scenario makes possible to inflate the plug with air, which allows for a fast inflation rate. There are several inflation methods that can be applied, such as releasing compressed gas, using a controlled chemical reaction, or with a phase-change system [6]. The selection of the best inflation method depends on the demands of the system to be protected.

On the other hand, if the RTS has to contain high pressures, which is the case of flooding threats, the plug must be inflated with a fluid. If such a large volume is inflated using high pressure air, the amount of energy stored in the plug is quite high, and the device is potentially dangerous in case of burst. A fluid inflation can require larger inflation times. However, in case of flooding, a strategically placed plug can allow sufficient time for inflation using water from a fire hydrant or pumping equipment.

3. VALIDATION TEST

The RTS presented above was already validated inside an actual rail transportation tunnel. The validation test consisted of sealing a tunnel section using an inflatable plug inflated at a low pressure (0.06 atm). This test represented the conditions of counteracting a possible threat, which can be mitigated by stopping the air flow inside the tunnel. Besides studying the performance of the RTS developed, primarily its deployment, sealing capacity, and inflation time, this test also demonstrated the feasibility of installing these systems in existing tunnels, complying with installation requirements, and minimizing or avoiding possible impact on tunnel serviceability.

3.1 Test Description

3.1.1 Inflatable structure and inflation method

The tunnel to be sealed in the validation test had a cross section similar to the one shown in figure 2. The geometry of the inflatable structure was defined according to the guidelines discussed in the previous section. It consisted of a cylindrical section, with a diameter of 5.6 m and a length of 3.7 m, closed with two spherical end caps. The diameter of each sphere was 7.3 m, and the height from the cylindrical junction to the crown was 1.3 m. The plug had two indentations, one to accommodate the flat portion of the tunnel ceiling and the other one to accommodate the sidewalk. Figure 5 shows a three-dimensional representation of the plug designed.

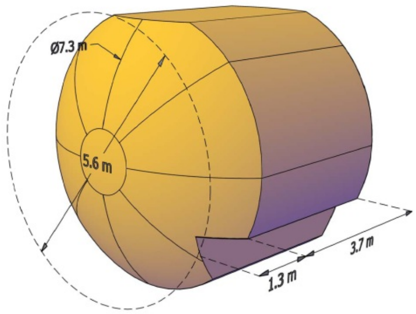

Figure 5: Three-dimensional representation of the inflatable structure manufactured

The plug was manufactured by Lightweight Manufacturing Inc. using a Ferrari Precontrain® 1002 fabric. This is a plain weave, 1100 denier, high tenacity polyester fabric, coated with PVC. According to the manufacturer specifications, the tensile strength of the fabric is 788 N/cm and the tear strength is 500 N. However, the critical strength of the material is defined by the tensile capacity of the seams, as these are the weakest regions in the inflatable structure. The seams of the plug were manufactured using a radiofrequency welding technique.

Rectangular fabric samples, both not-welded and welded at midspan, were cut with orientations in the fill and warp directions. Five specimens of each sample were tested following the ASTM D5035-06 standard [8, 9], to verify the strength properties provided by the manufacturer, and to obtain the weld strengths. The average values obtained for each case are shown in table 1. The results obtained from these tests show that the fabric is about 10% stronger in the warp direction than in the fill direction. The tests also show that for welded samples, in both directions, the fabric strength is reduced by nearly five percent. Therefore, the maximum fabric strength is defined by the welds in the fill direction, with an ultimate value of 736 N/cm, which is about seven percent less than the manufacturer's recommended value of 788 N/cm.

Table 1: Tensile test results obtained for the fabric used in the large scale test models

Ferrari Precontraint® 1002 used for the large scale tests		Break. Strength [N/cm]	Displacement [cm]
Non-welded sample (warp direction)	Mean Stand. Deviation	879.3 32.4	2.1 0.1
Welded Sample (warp direction)	Mean Stand. Deviation	836.8 32.2	2.3 0.5
Non-welded sample (fill direction)	Mean Stand. Deviation	763.7 19.6	2.2 0.1
Welded Sample (fill direction)	Mean Stand. Deviation	736.4 20.8	2.7 0.1

The maximum design stress to be applied to the fabric material was limited by a safety factor of four, to conservatively account for possible material defects, unexpected load increments and other unknowns. With this assumption, according to equation (1), the maximum inflation pressure was determined based on the limiting stress of the fabric at the spherical end cap, and by the radius of the end cap. This value is:

$$p = 2\sigma_{sph} / R = 2 \cdot (736 \div 4) / (730 \div 2) = 1.0\, N/cm^2 = 0.10\, atm$$

the low pressure at which the plug can be inflated made feasible to use air for this application. Also, considering that the RTS was not to be installed permanently in this demonstration test, there was no need for this purpose to devise a deliverable system that did not interfere with the tunnel normal operations. Based on these two conditions, the plug was inflated using a portable fan. The fan was capable of delivering pressures of 0.133 atm at a flow rate of 40 m^3/minute. With a total volume of approximately 110 m^3, the plug could be deployed and inflated in approximately three minutes.

The air inflation system used required two different fittings to be installed in the inflatable structure. One, with a diameter of 10 cm, was connected to the fan and was used to inflate the plug. The connection was made using a flexible hose. The second fitting had a diameter of 1.25 cm and was connected to a pressure gauge, which was used to read and control the internal pressure in the plug.

3.1.2 Test setup

In the validation test, the RTS described was used to seal an actual rail transportation tunnel. The test conducted not only consisted of installing and deploying the RTS, but also studied the different site modifications needed to install the RTS, and the feasibility of conducting this installation within the operational time constrains of a rail tunnel. The configuration of the test setup is shown in figure 6, which illustrates the different elements required to conduct the test: (1) the inflatable plug; (2) the hose connecting the plug to the fan; (3) the fan used for the inflation; and (4) the computer that controlled the flow rate supplied by the fan.

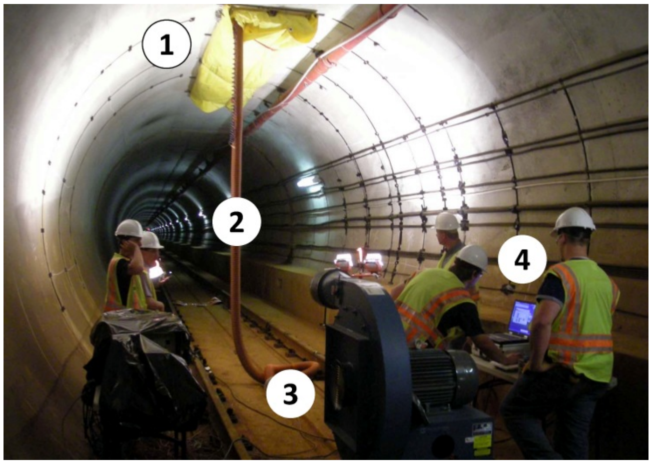

Figure 6: Components of the test setup at the rail transit tunnel

Because the tunnel section used to perform the test was in service, the installation was performed during limited time intervals in the evening. No major modifications were required in the tunnel. The site preparation was limited to recessing a couple of conduits that were detached from the wall. The plug was installed within a tunnel section in which there were no protruding elements, such as lights or hand-rails. These elements can reduce the sealing capacity of the plug and it is recommended to remove them from the section where the plug is to be installed.

The complete setup was performed in four evenings, working for approximately four hours each evening. On the first evening, the test elements and equipment were brought inside the tunnel. The plug was already packed and ready to be installed. During the second evening, the tunnel was prepared, illuminated, and cleaned; and the existing conduits were recessed to the tunnel wall. During the third evening, the inflatable plug was installed in the tunnel, attaching the supporting frame to the ceiling using eight bolts. Finally, on the fourth evening, the elements were connected, such as the plug to the fan and the fan to the computer. The experience at this site showed that the installation of the RTS can be accomplished quickly and without affecting the tunnel normal operations. It also showed that no major modifications may be required within the tunnel section and, once installed, the RTS does not contain any components that may block the transit in the tunnel and cause disruptions of its normal use. In the current test setup, shown in figure 6, the fan and the computer are interrupting the tunnel serviceability since they were installed over the track bed. However, in actual applications these elements do not have to be located close to the inflatable, as they can be installed in remote regions, such as stations, where they will not affect the tunnel normal use.

The test performed with the present concept sought verifying major performance characteristics of the RTS: (1) correct attachment and deployment, (2) inflation within a short time-span, (3) conformance to tunnel elements, and (4) sealing capacity of the inflatable within the tunnel section. The ability of the inflatable to seal the tunnel section was tested by releasing smoke on one side of the plug and observing the flow of smoke, or leakage, through regions on the opposite side. To force the smoke to move from one side of the plug to the other, an air flow was created using the ventilation system of the tunnel.

3.2 Test Results

3.2.1 Deployment of the RTS

The total deployment time to inflate the RTS was four minutes and 36 seconds, from the initial release of the inflatable structure to the moment at which it reached the targeted inflation pressure of 0.06 atm and sealed completely the tunnel section where it was installed. Figure 7 shows six different stages of this deployment. The inflation time required was higher than the predicted inflation time (based on the fan specifications), because of flow losses in the hose and because the fan was not running at its maximum speed. However, having the tunnel sealed in less than five minutes would make it possible to contain most of the threats that can affect the infrastructure.

This test also showed that the procedure developed to obtain a sequential deployment worked as expected. The nylon lines did not release the sidewalk section of the plug until the time of 3:23 minutes, at which moment the rest of the inflatable structure was perfectly accommodated within the cross section. When the stresses at the nylon lines reached their breaking strength and caused them to break, the indentation made in the plug was dropped over the sidewalk and it this cut-out fitted over the step as intended. Figure 8 shows the release sequence. The left picture corresponds to the instant just before the restraint mechanism was released, and the right picture corresponds to the instant just after it was released, when the nylon lines broke and the cut-out was placed in its correct position. The time difference between both pictures is 0.6 seconds.

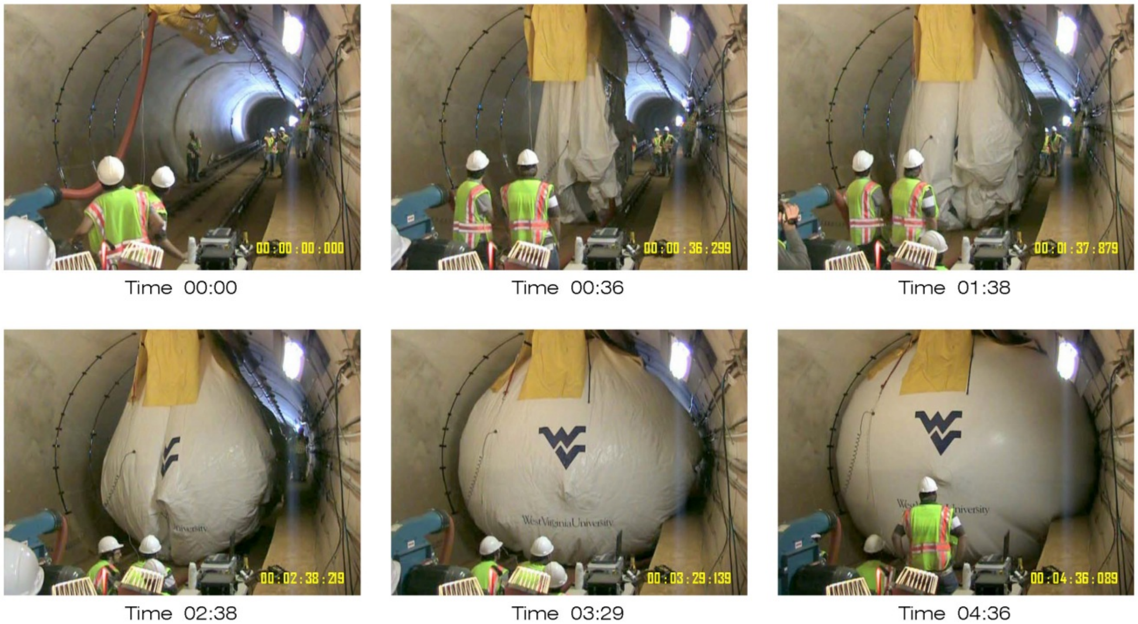

Figure 7: Deployment of the Resilient Tunnel System

Figure 8: Release of the restraint during the inflation process

3.2.2 Sealing capacity

The sealing capacity of the RTS was studied using a smoke test. This test consisted of releasing smoke on one side of the plug, while an air flow pulled the smoke out from the opposite side. The air flow was created using the ventilation system of the tunnel. If the RTS sealed the tunnel cross section perfectly, there would be no smoke on the opposite side; else the leakage regions would show the smoke passing through them.

The smoke test showed that the plug did not seal completely the tunnel section. Most of the smoke that leaked from one side to the other passed through a region around a ceiling water pipe. The test also showed some leakage around the rails, although the smoke flow in these regions was substantially less than the flow observed around the water pipe. No other leakage regions were observed during the test, not even along the pipes and conduits located over the walkway. Figure 9 shows how the plug conformed to the cross section, and how it adjusted to the different elements in the tunnel. With the exception of the water pipe, the inflatable conformed perfectly to all elements existing within the tunnel section.

Figure 9: Seal provided by the plug to the different elements existing in the tunnel

Although the RTS presented some leakage regions, these do not jeopardize its functionality, as the leakage obtained with the smoke test can be highly reduced by implementing small modifications around protruding elements within the tunnel section. All leakage was observed around the ceiling water pipe and the rails. These two elements present gaps that cannot be perfectly sealed by the inflatable plug due to their geometries (figure 10). However, these gaps can be sealed in the region where the RTS is installed, to improve the sealing capacity of the plug. Also, the plug will conform easily to the water pipe if its geometry is modified by building transition geometry around it. On the other hand, if the RTS has to contain a liquid (the case of having to prevent a tunnel flooding) some leakage can be accepted, as the liquid that passes through the plug can be drained with pumps, or with the tunnel's draining system.

3.2.3 Possible tunnel disruptions

It must be emphasized that the test performed showed that the RTS can be installed quickly and without major disruptions to the tunnel normal operations, and that its installation does not require major modifications within the tunnel section. Also, once installed, the RTS does not affect the tunnel's normal use. This is an important result as it supposes a significant advantage in relation to all other threat mitigation systems, which require complex constructions and long periods of work in the tunnel that make them quite costly, both in terms of construction costs and service disruption costs.

Figure 10: Existing gaps around rails and pipe

4. SUMMARY

This paper describes a new passive protection system, the Resilient Tunnel System, developed to mitigate threats in transportation tunnels. The RTS consists of installing one or more inflatable structures, or airbags, inside a tunnel. These inflatable plugs are capable of sealing the tunnel sections where they are installed, compartmentalizing the tunnel into strategic regions, within which possible threats can be contained. The threats that can be contained or minimized with the RTS are those that can flow through the tunnel system, such as fumes, deadly gases, fires and flooding.

The Resilient Tunnel System described in this paper was successfully manufactured and validated. The full scale demonstration test showed that it is possible to install and deploy the RTS in an actual transportation tunnel, without disrupting the normal tunnel operations, or requiring major modification within the tunnel. The deployment of the RTS can be performed quickly, as the inflatable structure is fully pressurized in less than five minutes. The inflated RTS can seal the tunnel and conform to its cross section, in spite of all protruding elements existing in it. And, although the smoke test performed to evaluate the sealing capacity of the RTS showed some leakage around a ceiling water pipe and the rails, these areas can be easily modified to improve the sealing capacity of the RTS. It is important to note that the correct placement of the inflatable structure around large protruding elements, such as the sidewalk, can be accomplished efficiently by the proposed sequential deployment of the plug, which worked very well in the validation test.

Having validated the RTS described in this paper, the application can be easily adapted to contain other type of fluids with more demanding response characteristics, such as pressurized water in case of flooding. In this case the inflation pressure in the plug must be increased substantially, compared to the inflation pressure required when containing gases. Larger inflation pressures will require using stronger fabric materials. When containing a flooding, another issue of concern is the axial stability of the plug within the tunnel section, as the axial force exerted by the head of water over the plug can be extremely high. The solution adopted relies on frictional forces developed between the plug and the tunnel wall. This resultant force can be increased by increasing the length of the plug.

Despite the challenges ahead, such as improving the sealing capacity of the plug or containing more demanding threats like floods, the successful results demonstrated by this first prototype of the Resilient Tunnel System makes it an outstanding option to improve tunnel safety, particularly when compared to other options available, which require more expensive and time consuming constructions efforts and considerable service interruptions of the system.

4.1 Acknowledgements:

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