Simulation of Controlled Deflation, Folding and Inflation of Large-Scale Confined Inflatable Structures

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Abstract: Transportation tunnels have been identified as particularly vulnerable to different threats such as propagation of toxic gases, or smoke originated by human activities, or flooding originated by extreme climatic events such as hurricanes and severe weather. The implementation of large-scale inflatable structures to plug specific locations of the tunnel system to minimize the consequences of the propagation of disastrous events is now possible. However, even with the successful results obtained in experimental evaluations, the development of simulations that can predict the performance of the inflatable in advance to reduce the number of experimental iterations is still essential. The finite element simulations presented in this work are focused on reproducing deflation, folding, and placement procedures for deployment and inflation of a large-scale inflatable from the ceiling of a tunnel segment. The results of the simulations showed that a very compact shape can be achieved by implementing a controlled deflation and a combination of translational and rotational planes to reach the final folded shape. Moreover, the implementation of passive restrainers to control the movement and release of the membrane during different stages of the simulations contributed to reach higher levels of local conformity of the inflatable to the tunnel perimeter, which also translated in a better sealing capacity of the inflatable to the tunnel profile.

Keywords: Abaqus, Deflation, Deployment, Finite Element Simulation, Folding, Inflation, Membrane, Tunnel, Inflatable Structures.

1. Introduction

The safety of transportation tunnels has become a great concern for transportation and government entities in the last decade (FHWA, 2003, TCRP, 2006, Rabkin, 2007). Transportation tunnels have been identified as particularly vulnerable to different threats originated by human activities or extreme climatic events. Flooding of tunnels have been particularly severe and produced significant damage to tunnel systems as reported by Inouye, 1992 or Zimmerman, 2014. Finding solutions to minimize the consequences of disastrous events has become critical to increasing the resiliency of transportation tunnel systems. One possible solution to contain the propagation of gases or flooding is the implementation of large-scale inflatable structures at specific locations of the tunnel system. When a threat happens, a sensing system detects it and triggers the activation of
an inflation system which can deploy, inflate and pressurize the inflatable structure in a few minutes (Barbero et al., 2013-a, Sosa et al., 2014-a). When the inflatable structure is completely inflated, it acts as a barrier held mostly by friction and isolates the compromised region to contain the threat. The feasibility of this concept was tested in a full-scale setup using an inflatable manufactured from a single-layer fabric material, as shown in Figure 1. In that test, the inflatable was deployed from the ceiling of a service tunnel and then fully inflated with air at relatively low pressure (less than 1 psig or 7 kPa) in approximately three minutes (Martinez et al., 2012).

Figure 1. Demonstration of Feasibility (Martinez et al., 2012).

In the last few years, extensive experimental evaluations were conducted to evaluate and understand key aspects of the operation and mechanical behavior of large-scale inflatable structures (Fountain, 2012, Barbero et al., 2013-b, Sosa et al., 2014-a/b/c, Sosa et al., 2017). From the operational point of view, experimental results showed that the implementation of a large-scale inflatable for sealing one or more segments of a tunnel system can be divided into three main phases: Phase 1, preparation and installation; Phase 2, initial deployment and inflation at low pressure; Phase 3, pressurization of the inflatable structure to contain the pressure of the threat, either gas or water. In Phase 1, the inflatable structure is folded and placed within a portable container that is then transported to a specific location of the tunnel segment and pre-installed. Phase 2 starts when a sensing system detects a threatening event. The sensing system activates the automatic opening of the container allowing the initial unfolding and deployment followed by the activation of inflation system. When the inflatable is in place, Phase 3 starts with the pressurization to ensure that the inflatable will remain in place when subject to the external pressures (Sosa et al., 2017).

The main objective of this work is to create Finite Element (FE) models able to simulate the procedures for the preparation (Phase 1) and deployment and inflation (Phase 2) of the single layer inflatable used in the tests reported by Martinez et al., 2012. Using the techniques presented in Sosa et al., 2016-a/b as a starting point, this work explores new ways for better control of the
membrane of the inflatable since it plays an important role on the final global and local conformity of the inflatable to the tunnel. This work also aims to demonstrate that using a simplified geometry for the inflatable it is possible to achieve similar or higher levels of local conformity as those obtained using a fitted shape of the inflatable adopted in the experiments reported by Martinez et al., 2012. In particular, the FE models presented in this work were developed to simulate the following operations:

- Folding methods that follow the procedures implemented experimentally, including the implementation of a controlled deflation to reach a flat shape and, the implementation of a folding procedure for the flat shape that minimizes the storage volume.
- Initial deployment and inflation, which required the definition of placement procedures of the folded shape in the storage area of the tunnel cross-section, and the definition of a sequence of deployment and inflation under confined conditions.

2. Model Generation

2.1 Modeling Tools

The Simulia Finite Element simulation package was implemented in this work (Abaqus, 2014). In particular, the geometry and meshing of the model were generated using Abaqus/CAE. All the nodes and the element were later renumbered with HyperMesh tools (Altair, 2016), and the model properties were compiled in an Abaqus input file (.inp) to make the simulation work more efficient. The Abaqus .inp file included material properties and the mechanical properties needed for the proper definition of the structural model. In this work, all the models were solved with Abaqus/Explicit, and Abaqus/Viewer was used to visualize and post-process the simulation results.

2.2 Geometries

The two main components of the model are the inflatable structure and the tunnel segment representative of the confined environment in which the inflatable will be installed and inflated. Additional components are the “base” which is representative of the floor where the folding procedures take place and folding planes used to simulate the folding procedures implemented experimentally (Martinez et al., 2012).

The inflatable structure modeled in this work consists of a cylinder with two spherical end caps. The model of the inflatable follows the dimensions and material properties of the full-scale prototype used in the experiments reported by Martinez et al., 2012. The cylindrical perimeter of the inflatable is designed to be larger than the perimeter of the tunnel in order to account for the possibility of bridging around the corners and the presence of other elements that could interfere with the local conformity of the inflatable to the tunnel perimeter.

The generation of the FE model of the inflatable structure was completed during the pre-processing in which the geometry of the model, material properties, element type and contact interaction properties were defined. The initial geometry of inflatable structure was created using
three-dimensional deformable shell through Abaqus/CAE. The shell surface was then partitioned in several auxiliary surfaces as shown in Figure 2. The partitions on the cylindrical part of the inflatable structure were created to define folding surfaces and folding lines that were very useful as reference lines at the different stages of the simulation. Additional surface partitions were created on the spherical end caps to have a more uniform mesh. The membrane of the inflatable was modeled using M3D3 membrane elements (Abaqus, 2014).

The FE model of the tunnel, base and folding planes were created via three-dimensional rigid shell surfaces generated in Abaqus/CAE. Since these surfaces are considered non-deformable, they were meshed using linear quadrilateral rigid elements R3D4 (Abaqus, 2014). The meshes of the tunnel, base, and folding planes are shown in Figure 3.

![Figure 2. Inflatable structure, FE initial geometry, and partitions generated using Abaqus/CAE.](image)

![Figure 3. Meshes of folding planes (left), base (center) and tunnel segment (right).](image)
3. Controlled Deflation, Folding, Placement and Confined Inflation

3.1 Controlled Deflation (Case 0)

The objective of the simulation of a controlled deflation is to reach the flattest possible shape with the minimum amount of wrinkles on the flattened membrane in order to minimize the volume of the final folded shape. The simulation started with the nominal shape of the inflatable structure subjected to an internal pressure equal to the gravity pressure to balance the external load due to the application of gravity. Modeling of the internal pressure required the definition of a fluid cavity to represent the volume being filled by the gas (Input File Usage: *FLUID CAVITY). The fluid cavity was defined by the internal volume of the inflatable structure. The fluid cavity also required the definition of a cavity reference node (Input File Usage: *NODE). The internal pressure was imposed as a boundary condition to the cavity reference node (degree of freedom 8) (Input File Usage: *BOUNDARY). Since the development of large wrinkles depends on how fast the internal pressure is reduced, the controlled deflation was performed using a shallow slope for the decreasing ramp function (Input File Usage: *AMPLITUDE). Although the controlled deflation was performed in one step, the simulation was stopped every four iterations to have better control of the collapse of the membrane. After each interruption, the coordinates of the resultant shape were exported first to Abaqus/CAE and then to Hypermesh to inspect the mesh and detect if the membrane elements were affected by inter-element penetrations and intersections, and in such case, correct them before continuing with the simulation once again. This process was denominated “cleaning process,” after which, the controlled deflation with the corrected mesh continued using the same initial conditions of pressure ($P_{\text{internal}} = P_{\text{gravity}}$) with the same decreasing ramp. The sequence of the controlled deflation is shown in Figure 4.

![Figure 4. Sequence of controlled deflation.](image)
3.2  Folding and Placement

The flattened shape of the inflatable structure obtained at the end of the controlled deflation technique was the starting point of the folding sequence. The folding sequence included the definition of two rotating planes (FP1, FP2) and two translational planes (FP3, FP4) as shown in Figure 5(a). The partial folds of the membrane of the inflatable were created by imposing rotational ($\varphi_x = 4$, $\varphi_y = 5$, $\varphi_z = 6$) and translational ($u_x = 1$, $u_y = 2$, $u_z = 3$) boundary conditions to the reference nodes of the folding planes as illustrated in the sequence of Figure 5(b) to 5(f). The folded shape obtained at the end of the folding sequence was used to perform the placement inside the tunnel segment as illustrated in the sequence of images of Figure 6. The placement process began with the folded shape pre-positioned at the center of the tunnel, as illustrated in Figure 6(a) and continued by imposing rotational and translational boundary conditions to the reference node of the folded shape defined as a rigid body (Input File Usage: *COUPLING → *KINEMATIC) as illustrated in Figure 6(b) to 6(e).

Figure 5. Folding sequence, main folding steps, top view (folding planes removed for clarity in images (b) to (f)).

Figure 6. Placement process.
3.3 Initial Deployment and Confined Inflation

The sequence of deployment and inflation started with the folded shape positioned in the storage area on the ceiling of the tunnel as shown in Figure 6(e). The tunnel was assumed to be a rigid body fixed in the X, Y, and Z global directions. The simulation was performed in one step in which gravity and the inflator system were activated sequentially. Gravity (Input File Usage: *DLOAD) was applied as an impulse at the beginning of the simulation and the inflator (Input File Usage: *FLUID INFLATOR → *FLUID INFLATOR PROPERTY → *FLUID INFLATOR MIXTURE) was activated with 2 seconds of delay to reproduce experimental results reported by Martinez et al., 2012. The folded shape was connected to the ceiling of the tunnel using three lines of nodes defined along the cylindrical portion. These nodes represented the ties that fastened and restrained the inflatable structure to the ceiling of the tunnel profile. The simulation results corresponding to the initial deployment from the ceiling of the tunnel and subsequent inflation is illustrated in Figure 7. These simulation results are compared to a sequence of images captured during the experiments reported by Martinez et al., 2012.

Results illustrated in Figure 7 show that the simulation of initial deployment followed the overall shape and membrane behavior seen in the experiments. Also, the global conformity of the inflatable to the tunnel and the inflated shape at the end of the simulation were both similar to the shape observed in the experiments. However, considering the local conformity, the simulation showed two clear contact gaps on the right corners of the tunnel profile due to the lack of uniform distribution of the membrane material. Based on these results, an enhanced technique was developed to improve the lack of local conformity. This enhanced technique included the controlled deflation described previously with better control of the collapse of the membrane of the inflatable, due to the application of the gravity load. In this enhanced technique, the membrane of the inflatable was controlled not only by a decreasing internal pneumatic pressure but also by
applying additional displacement boundary conditions to specific lines and portions of the membrane to form initial pre-folds to remove wrinkles further and improve the membrane distribution over the deflated shape.

4. Controlled Deflation Including Pre-folding Steps

Two cases of controlled deflation including pre-folds were simulated: the first one, Case A, included only one pre-fold, and the second one, Case B, included two pre-folds. Case A was developed to simulate the technique of the controlled release of the membrane similar to the one implemented in the experiments reported by Martinez et al., 2012 and in Sosa et al., 2016. Case B was created to show the potential of this enhanced technique and to emphasize the possibility of achieving a higher level of local conformity of the membrane in more intricate tunnel profiles.

The position of the initial pre-folds was dictated by the position of folding surfaces of the membrane that did not conform to specific locations (corners) in the tunnel profile at the end of the inflation as shown in Figure 7(f).

4.1 Case A

The initial shape used at the beginning of the simulation was the initial nominal shape of the inflatable structure shown in Figure 2. The initial single pre-fold, as mentioned above, was chosen considering the position of the folding surfaces (colored bands in Figure 2) necessary to cover the critical corners of the tunnel profile. In order to achieve a symmetric flat deflated shape, another pre-fold was created on the opposite side of the first pre-fold with the purpose of obtaining an equal distribution of the membrane material as shown in Figure 8. Translational boundary conditions were applied to the reference lines to guide the formation of the pre-folds as illustrated in the sequence of images of Figure 9. Once the two initial pre-folds were formed, as illustrated in Figure 9(e), equally spaced nodes located at the bottom and the top lines were linked with connector elements (Input File Usage: *ELEMENT, TYPE = CONN3D2, ELSET= name) to maintain the lines close to each other which contributed to maintain the shape and size of the pre-fold for the rest of the controlled deflation.

![Figure 8. Controlled deflation, reference lines (TL top line, CL center line, BL bottom line)](image-url)
4.2 Case B

Case B included the two pre-folds created in Case A, plus a third pre-fold. The initial shape used at the beginning of the simulation of Case B was the shape illustrated in Figure 9(d) as shown in Figure 10. Translational boundary conditions were applied to the reference lines to guide the formation of the third pre-fold as illustrated in the sequence of images of Figure 11. Once the third pre-fold shown in Figure 11(c) was formed, equally spaced nodes located on the top (TL) and bottom (BL) lines of the fold were linked with connector elements to maintain the lines close to each other. As in Case A, connecting these lines contributed to maintain the shape and size of the third pre-fold for the rest of the controlled deflation.
4.3 Folding and Placement

The flattened shapes obtained at the end of the controlled deflation with the inclusion of pre-folds corresponding to Case A and Case B were folded imposing translational and rotational boundary conditions to the folding planes FP1 and FP2 illustrated in Figure 12. The folding procedure was the same for both cases. Six nodes on the top and the bottom edges of each pre-folding lines were restrained using connector elements to avoid sliding of the membrane material during the folding process to prevent distortion of the pre-folds.

Regarding final folded volume, Figure 13 compares two folded shapes positioned on the ceiling of the tunnel. Figure 13(a) shows the folded shape obtained without the inclusion of pre-folds (Case 0), whereas Figure 13(b) shows the folded shape obtained using the pre-folds (Case A and B). From Figures 13(a) and 13(b), it is possible to see a significant reduction of the overall folded volume and a more uniform distribution of the membrane material along the total longitudinal length of the inflatable. The reduction of the thickness of the folded shape is also shown in Figure 13. For Case 0, the overall thickness was 0.32 m, and for Cases A and B, the overall thickness was 0.18 m, which is almost half of Case 0.
4.4 Confined Inflation with Controlled Release of Membrane

The simulation of the deployment and inflation implementing a controlled release of the membrane material was similar to the process described previously (Case 0) except for the
presence of the passive restrainers modeled with connector elements (Input File Usage:
*ELEMENT→ *CONNECTOR SECTION→ *CONNECTOR BEHAVIOR→ *CONNECTOR
ELASTICITY→ *CONNECTOR FAILURE). Case A included only one pre-fold to control the
release of the membrane, and Case B included two pre-folds for controlling the release of the
membrane. The simulation results in the last stage of the inflation ($t = 175$ sec to $t = 205$ sec)
corresponding to Cases 0, A and B are illustrated in cross-sections of Figure 14. The sequence of
images corresponding to each case illustrates the following aspects of the membrane behavior in
terms of local conformity of the inflatable to the corners of the tunnel perimeter:

- In Case 0, as indicated previously, the distribution of the membrane material was not
  uniform around the tunnel perimeter. This non-uniformity is manifested by the presence
  of wrinkles on the floor of the tunnel. Moreover, the non-uniform distribution of
  membrane material led to the formation of bridging of the membrane material in at least
  two corners of the tunnel profile.

- In Case A, simulation results show that inflatable was able to conform to the upper right
corner, but it was not able to fill the lower right corner of the tunnel. Comparing Case 0
  and Case A, it is possible to observe an improvement in the conformity on the upper right
corner of the tunnel that is attributed to the inclusion of the pre-fold which released upon
  breakage of the passive restrainers at the end of the inflation.

- In Case B, simulation results show a remarkable improvement in the local conformity in
  both corners of the tunnel profile. This improvement is attributed to the inclusion of two
  pre-folds and the release of the membrane contained in both pre-folds upon nearly
  simultaneous breakage of the passive restrainers at the end of the inflation.

In order to quantify the global conformity and to highlight the improvements reached with the
implementation of pre-folds and the controlled release of the membrane, the contact areas
achieved at the end of the simulations in Cases 0, A and B are plotted in Figure 15.

Figure 15 shows that at the end of the simulation, the magnitude of the contact area for Cases 0, A
and B exceeded the nominal contact area (NC) of the cylindrical portion of the inflatable in the
tunnel evaluated considering the cylindrical region having the same radius of the tunnel. Table 1
summarizes the percentages of improvement achieved in the three cases. The improvement in the
contact area can be attributed to two factors: 1) The confining effect produced by the tunnel in
which part of the spherical end caps become part of the cylindrical portion of the inflatable, and 2)
the controlled release of the membrane during the last stage of the inflation process, which
contributes to achieving a better local conformity of the membrane material to the tunnel corners.

The percentage of improvement due to confining effect is calculated taking into account the
nominal contact area of the cylindrical portion of the inflatable in the tunnel and the contact area
of Case 0, which did not include any pre-folds or passive restrainers. The percentages of
improvement due to the controlled release of the membrane corresponding to Cases A and B are
calculated taking into account the contact area of Case 0 as a point of comparison. The increase in
the contact area seen in these two cases (A and B) are attributed to the better local conformity in
the corners of the tunnel profile as illustrated in Figure 14.
Figure 14. Release of the membrane, comparison of simulation results for Case 0, Case A and Case B.

Figure 15. Time history of contact area for Cases 0, A and B.

<table>
<thead>
<tr>
<th>Case</th>
<th>Contact Area [m²]</th>
<th>% of Increase</th>
<th>Improvement due to</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>57.7</td>
<td>-</td>
<td>Nominal Contact area</td>
</tr>
<tr>
<td>0</td>
<td>60.8</td>
<td>5</td>
<td>Confining effect</td>
</tr>
<tr>
<td>A</td>
<td>66.8</td>
<td>15</td>
<td>Confining effect + release of membrane</td>
</tr>
<tr>
<td>B</td>
<td>67.3</td>
<td>16</td>
<td>Confining effect + release of membrane</td>
</tr>
</tbody>
</table>
5. Conclusions

A procedure for simulating a controlled deflation, folding, deployment, and inflation of a large-scale inflatable structure for sealing a tunnel cross-section has been outlined in this paper. The simulation steps of the proposed procedure can closely reproduce the steps of the work implemented experimentally including the preparation of the inflatable, installation in the tunnel section as well as the initial deployment and inflation. The simulation results are helpful to predict the performance of the inflatable in advance and minimize the number of experimental iterations. The implementation of controlled deflation techniques with the addition of pre-folds held by passive restrainers produced a significant improvement in the resultant deflated shape producing the reduction in the amplitude of wrinkles and also improving the distribution of the membrane over the surface of the resultant deflated shape. This technique also contributed to minimize the storage volume when installed on the ceiling of the tunnel profile.

The inclusion of passive restrainers contributed not only to preserve the position of the pre-folds during the folding procedure but also to produce a gradual release of the membrane during the latter stages of the inflation process. Simulation results showed the gradual release of the membrane material during the inflation contributed to reach higher levels of local conformity by closing gaps in critical corners of the tunnel perimeter, which translated in an increased contact area. Simulation results also showed that the simplified geometry of the inflatable adopted for the simulations presented in this work can reach similar levels of global and local conformity as the levels reached with a fitted shape of the inflatable used in experimental evaluations. These results suggest that with the proper introduction of controlled deflation, pre-folds and passive restrainers, an inflatable with a cylindrical shape could virtually conform to any tunnel profile.

6. References


