Study of a Honeycomb-Type Rigidified Inflatable Structure for Housing

Ritesh A. Khire

Steven Van Dessel

Achille Messac

Anoop A. Mullur

Corresponding Author

Achille Messac, Ph.D.
Distinguished Professor and Department Chair
Mechanical and Aerospace Engineering
Syracuse University, 263 Link Hall
Syracuse, New York 13244, USA

Email: messac@syr.edu
Tel: (315) 443-2341
Fax: (315) 443-3099
https://messac.expressions.syr.edu/

Bibliographical Information
Abstract: This paper presents a parametric study aimed at uncovering general design principles that govern the structural performance of honeycomb-type rigidified inflatable structures (RIS) as load-bearing wall systems for use in residential housing. This study involves the use of finite element modeling and optimization. A series of honeycomb-type RIS wall systems, each comprising different honeycomb cell sizes, are examined. The problem at hand is stated in the form of minimizing material volume subject to: permissible stress, maximum allowable deflection, and membrane thickness. The optimization results help identify optimal design configurations for given sets of loading conditions and material properties. The effects of various design parameters, such as cell size, material properties, and membrane thicknesses, are discussed. The performance of honeycomb-type RIS wall systems is compared with that of rectilinear-type RIS wall systems, which were studied previously. The work presented makes a significant step in establishing the feasibility of RIS for housing applications.

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CE Database subject headings: Inflatable structures; Honeycomb structures; Finite elements; Buckling; Composite materials; Housing.

Introduction

Rigidified Inflatable Structures

Rigidified inflatable structures (RIS) are thin-walled structures, made of initially flexible membranes that take their solid shape upon pneumatic inflation, and thereafter become rigid and maintain their shape without the aid of internal pressure (Van Dessel et al. 2003a). In their final rigidified state, RIS are thin-shell composite structures that have load-bearing capacity. Some of the potential benefits of RIS technology over conventional construction techniques include: (1) lower material usage; (2) shorter manufacturing time; (3) compact stowed volume, allowing convenient transportation; (4) faster and safer construction; and (5) ability to easily build complex structures. These benefits have prompted the development of RIS technology for space applications; for example, to construct space antennas and large support structures (Kennedy 1996; Freeland et al. 1998). A review of RIS technology, including applications and possible materials, is provided by Jenkins et al. 1998, and Cassapakis and Thomas 1995. In earlier studies, we have examined the structural and economic feasibility of RIS technology for use in residential housing (Van Dessel et al. 2003b; Messac et al. 2004). The focus of these earlier studies was on the design and optimization of a relatively simple rectilinear-type load-bearing wall system. The aim of the current study is to assess the structural viability of various honeycomb-type RIS load-bearing wall systems for use in housing (Fig. 1). The performance of honeycomb-type RIS wall systems is compared with that of rectilinear-type RIS wall systems (Van Dessel et al. 2003b).

Honeycomb-Type RIS Wall Systems

Honeycomb sandwich structures are widely used as lightweight high-strength structural members in automobile and airplane components. Honeycomb sandwich structures typically consist of a hexagonally shaped core sandwiched between two flat laminate skins. The general design principles of these conventional honeycomb sandwich structures are well established (Gibson and Ashby 1997). Honeycomb-type RIS wall systems differ significantly from these conventional honeycomb sandwich structures. Some of the differences are: (1) the front and back membranes of the RIS honeycomb cell naturally assume a curved topography due to the inflation process, as illustrated in Fig. 1, where two generic cell columns are represented. This topography depends on the inflation pressure, membrane properties, and cell size; and (2) the RIS honeycomb cell size is much larger than that of conventional honeycomb structures to facilitate fabrication. In this study, we are interested in using RIS honeycomb-type load-bearing wall systems for housing. In such applications, the honeycomb-type RIS wall will be subjected to: (1) gravity loads when supporting a roof or floor; (2) wind loads; and (3) shear loads. These loading conditions differ significantly from those of conventional honey-
comb sandwich structures that are primarily designed to resist bending. In this paper, we address the first two types of loads.

The specific characteristics of honeycomb-type RIS wall systems do not allow the use of the general design principles established for conventional honeycomb structures. One of the main objectives of this study is to uncover similar design principles that govern the structural performance of this class of structures. To accomplish this task, we perform a parametric study on a series of honeycomb-type RIS wall systems that differ in their geometric configurations and material properties. This study involves using finite-element modeling and optimization. The results of this study are intended to help us assess the feasibility of honeycomb-type RIS wall systems for use in residential construction. Also, the optimization results help identify the optimal design configuration for a given set of loading conditions and material properties.

This paper is organized as follows. The second section presents the strategy used in developing the finite element models for the various honeycomb-type RIS wall systems. It also provides the details regarding the different loading conditions and material properties. The third section describes the optimization based design process. In the fourth section, we discuss the performance of the various honeycomb-type RIS wall systems, and compare their performance with that of the rectilinear-type RIS wall systems studied previously (Van Dessel et al. 2003b). Conclusions are provided in the final section.

Modeling of Honeycomb-Type RIS Wall

In this section, finite-element models are developed for honeycomb-type RIS wall systems with various hexagonal cell sizes. A description of the modeling approach follows.

Model Development

Fig. 1 provides a generic illustration of a honeycomb-type RIS wall system. Fig. 2 depicts an isometric view of a single hexagonal cell. Each honeycomb cell is comprised of: (1) a front membrane (hexagonal); (2) a back membrane (hexagonal); and (3) six interior membranes (rectangular). Six different design configurations are investigated, each having a different hexagonal cell size, denoted by \( s \) in Table 1 and Fig. 2. The wall thickness is \( 0.3 \) m for all design configurations, which is consistent with the previous study on rectilinear-type RIS wall systems (Van Dessel et al. 2003b).

The inflation process will shape and deform the membranes of the honeycomb-type RIS wall. These deformations become permanent after the RIS membrane becomes rigid. The resultant structure consists of self-sustained rigidified thin membranes that maintain their shape without the aid of internal pressure. In this paper, we have not modeled the inflation process explicitly. Since, the inflation pressure is not required once the membranes become rigid, modeling of the inflation process does not affect the final analysis of the RIS-honeycomb wall. However, the following assumptions are made to account for the effects of the inflation process: (1) The front and back membranes assume a curved topography due to the inflation pressure. These membranes are modeled with an out-of-plane curvature in the transverse direction (along the \( Z \) direction). This curvature protrusion is assumed to be one fifth of the hexagonal cell size (Fig. 2). This value was deemed realistic, and was adopted for aesthetic reasons. Its magnitude will depend on such factors as cell size, membrane thickness, and inflation pressure. (2) Since the interior membranes are shared by two adjacent cells, the inflation-induced deformations of these membranes practically cancel one another. Hence, we model them as planar surfaces (without any initial curvature) as shown in Fig. 2. (3) Although the interior membranes at the edges of the wall will also undergo deformation due to the inflation process, we have neglected these inflation-induced edge deformations.

As stated in the previous paragraph, we have not modeled the inflation process explicitly. However, some of the process parameters, such as consistency of the inflation pressure during the rigidification process and rate of inflation, are expected to affect material and geometrical properties of the rigidified membranes. In addition, the rigidified membranes might be subject to creep strain over time, depending on temperature and stress levels (Mallick 1993). In the current paper, we do not take into account the effects of these process parameters on material properties. How-

### Table 1. Design Cases

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Cell size</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E=3 ) GPa, ( \sigma_y=30 ) MPa (A)</td>
<td>( 1,000 ), ( 0.575 )</td>
</tr>
<tr>
<td>( E=10 ) GPa, ( \sigma_y=100 ) MPa (B)</td>
<td>( 10,000 ), ( 0.433 )</td>
</tr>
<tr>
<td>( E=30 ) GPa, ( \sigma_y=300 ) MPa (C)</td>
<td>( 20,000 ), ( 0.289 )</td>
</tr>
</tbody>
</table>

\( \sigma_y \) = Young's modulus, \( \sigma_y \) = yield stress.
ever, we note that detailed analysis of these effects constitute important potential areas of studies. In the next subsection, we discuss the development of the finite-element model of the honeycomb-type RIS wall.

Finite Element Modeling

A finite-element (FE) model is generated for each of the honeycomb-type RIS wall configurations, as discussed above, using the finite-element analysis and optimization program, GENESIS (Vanderplaats 2001). The FE mesh is generated using four-node quadrilateral plate elements (CQUAD4) and three-node triangular plate elements (CTRIA3). These plate elements have in-plane and bending stiffnesses. The element mesh density was validated by altering the size of the elements and observing the stability of the results for deflections, stresses, and buckling. We observed that the results do not change appreciably when we change the mesh density from six elements to a higher number of elements along each side of the hexagonal cell. In particular, we monitored the variation in the maximum deflection and stress for different mesh densities. A FE mesh density of six elements or more along each side of the hexagonal cell was deemed adequate.

Figs. 3 and 4 represent the applied boundary conditions and external loads. To reduce the computational requirements, symmetry boundary conditions are applied to all the nodes located along the right edge of the wall, as shown in Fig. 3. The results obtained by analyzing these partial models are extrapolated to yield the final results for a 10 m long wall. The translational degrees of freedom (DOFs) along the X, Y, and Z directions are fixed for all the nodes located on the bottom edges of the wall. Also, for all the nodes along the top edges of the wall, the translational DOFs along the X and Z directions are fixed. The DOFs for all other nodes are released. The models contain on the order of 50,000 DOFs. We note that a nonlinear FE analysis may be required to accurately estimate the maximum stress and deflection of the honeycomb-type RIS wall. However, in the present study, we limit ourselves to a linear elastic analysis for comparing the relative performance of the various design cases under the simplifying assumptions, stated previously. Thus, in keeping with the scope of this preliminary investigation, we use a linear elastic FE analysis to estimate the maximum stress and deflection of the RIS-honeycomb wall.

Preliminary analysis revealed that local buckling was prominent in the vicinity of the bottom edge of the wall. The areas where local buckling occurs are indicated in Fig. 5. We observed that, by locally increasing the membrane thickness in these sensitive areas, the required membrane thicknesses in all other areas of the wall could be substantially decreased. Accordingly, an additional 5 mm-thick supporting membrane along this bottom region of the wall is incorporated in the FE models. This supporting plate is a component that negotiates between the honeycomb-type

Fig. 3. Schematic representation of finite-element model of honeycomb-type RIS wall system

Fig. 4. Boundary conditions and external loads on wall (section view)

Fig. 5. Region of local buckling and conceptual design of support structure
wind load of 2,000 N/m$^2$ is applied as a uniformly distributed wall is an integer. Table 2 provides the correspondence between the various materials are summarized in Table 1, where given in Mallick properties were estimated based on a simple rule of mixtures, and material properties are assumed for all three materials. These properties were estimated based on a simple rule of mixtures, given in Mallick (1993). The specific mechanical properties for the various materials are summarized in Table 1, where $E$ denotes the Young’s modulus, and $\sigma_y$ the yield strength. Note that these values represent the properties of the RIS membrane in its rigidified state.

**Material Properties**

Three different materials are considered for the RIS membranes: (1) nonreinforced polymers; (2) lightly fiber-reinforced polymers; and (3) moderately fiber-reinforced polymers. Equivalent isotropic material properties are assumed for all three materials. These properties were estimated based on a simple rule of mixtures, given in Mallick (1993). The specific mechanical properties for the various materials are summarized in Table 1, where $E$ denotes the Young’s modulus, and $\sigma_y$ the yield strength. Note that these values represent the properties of the RIS membrane in its rigidified state.

**External Loads**

In the present study, we consider two types of loads acting on the honeycomb-type RIS wall: (1) wind load, and (2) vertical load. A wind load of 2,000 N/m$^2$ is applied as a uniformly distributed pressure acting on the structure in the negative Z direction, as shown in Figs. 3 and 4. This wind load represents extreme conditions occurring at coastal areas (BOCA 1996). Vertical loads are applied in the negative Y direction. Three different vertical loading scenarios are investigated; namely, 1,000, 10,000, and 20,000 N/m. These scenarios represent typical loading conditions for residential walls, such as roof or floor loads. The total vertical load is uniformly distributed over all the peripheral nodes along the top edge of the wall, as shown in Fig. 3. Table 1 summarizes the three loading cases.

**Design Cases**

Table 1 provides the various design cases that are investigated, including the various hexagonal cell sizes. The cell sizes ($s$) are selected such that the number of cells along the 3 m height of the wall is an integer. Table 2 provides the correspondence between the cell size and the number of cells along the 3 m height of the wall. Each wall configuration is optimized for the various material and load combinations. This results in a total of $3 \times 3 \times 6$ (materials $\times$ loads $\times$ cell sizes)$=54$ design cases. A description of the optimization effort is provided in the next section.

**Optimization Based Design**

An optimization based design approach is used to obtain the optimal design configurations for the various honeycomb-type RIS wall systems described in the previous section. This section describes the details of the optimization problem, such as the design variables, the design constraints, and the objective function.

**Design Variables**

Three design variables are considered for the optimization of the honeycomb-type RIS wall. These are: thickness of the (1) front membrane ($t_1$); (2) back membrane ($t_2$); and (3) interior membranes ($t_3$). Membrane thicknesses are bound between 0.5 and 5 mm.

**Design Constraints**

Three design constraints are enforced as part of the optimization problem. These constraints are: the maximum deflection of the wall, the maximum stress induced in the rigidified membranes, and the buckling load factor. A discussion of these constraints follows.

**Deflection**

The present study is concerned with the design of various honeycomb-type RIS wall systems for use in housing. No building codes exist that govern deflection limits for these types of structures. We make the reasonable assumption that building codes used for wood light-framing systems could be used in the case of honeycomb-type RIS wall systems. The 1996 BOCA National Code (BOCA 1996) defines allowable limits for the deflection applicable to wood light-framing systems. This code requires that the deflection of the structural members, when finished with nonbrittle materials, should be less than 1/120th of the height of the wall when it is subjected to the design wind pressure. We impose a similar constraint on the deflection of the RIS wall system. Accordingly, the upper limit for the deflection $d_y$ measured along the $Y$ direction and the deflection $d_z$ measured along the $Z$ direction, as shown in Fig. 4, is 0.025 m.

**Induced Stress**

The maximum von Mises stress ($\sigma_m$) induced in the rigidified membranes of the honeycomb-type RIS wall systems is used as a design constraint. The yield strength ($\sigma_y$) of the material is used as the upper limit.

**Buckling**

Buckling is a likely mode of failure for thin-walled composite structures (Papangelis and Hancock 1995). Hence, buckling is used as one of the design constraints for the honeycomb-type RIS wall. GENESIS performs a global buckling analysis, whose result also provides local information, and points to the part of the structure that is weakest in buckling. The result of this buckling analysis is a buckling load factor, $b$, for the applied load. A buckling load factor of less than 1 indicates that the structure fails in buckling. A buckling load factor that equals 1 represents the critical loading case. Hence, the buckling load factor is constrained to be greater than, or equal to 1. This is a coarse indicator of the buckling behavior of the honeycomb-type RIS wall. A more accurate limit for the buckling load factor should be evaluated in future studies, which could include such effects as material and loading imperfections, and irregularities in the manufacturing and inflation processes.

<table>
<thead>
<tr>
<th>Table 2. Required Number of Cells along 3 m Height of the Wall</th>
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<tbody>
<tr>
<td>Number of cells along height</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
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<td>6</td>
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<td>8</td>
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<td>10</td>
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<tr>
<td>12</td>
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</table>
Objective Function

In this study, it is assumed that the total cost of constructing a honeycomb-type RIS wall is proportional to the amount of material required for a given material. Accordingly, the total material volume of the wall is selected as the objective function, and it is minimized.

Optimization Problem Statement

The optimization problem for the honeycomb-type RIS wall is formulated as shown below

$$\min_{t_1, t_2, t_3} v$$  \hspace{1cm} \text{(1)}$$

subject to

$$\sigma_v \leq \sigma_y$$  \hspace{1cm} \text{(2)}$$

$$d_y \leq d_{\max}$$  \hspace{1cm} \text{(3)}$$

$$d_z \leq d_{\max}$$  \hspace{1cm} \text{(4)}$$

$$b \geq 1$$  \hspace{1cm} \text{(5)}$$

where $v =$ material volume of the honeycomb-type RIS wall; $\sigma_y =$ yield strength of the material; $d_{\max} =$ maximum allowable deflection in the wall; and $t_{\min}$ and $t_{\max} =$ lower and upper bounds on the front ($t_1$), back ($t_2$), and interior ($t_3$) membrane thicknesses, respectively. Each design case of the honeycomb-type RIS wall, described in the previous section, is optimized individually according to the details given in this section. Optimization results obtained for each model are discussed in the next section. We note that the above optimization formulation is fully deterministic, and that a robust optimization formulation would be helpful in a more advanced study.

Results and Discussion

Figs. 6–8 represent the optimal (minimal) volumes of the various honeycomb-type RIS wall systems, for Materials A, B, and C, respectively. Figs. 9–11 show the effect of the Young's modulus ($E$) on the optimal thicknesses of the front, back, and interior rigidified membranes, respectively, when the wall is subjected to a vertical load of 20,000 N/m. Table 3 provides all the optimal parameters for the honeycomb-type RIS wall systems, for different cell sizes, loading conditions, and material properties. In Table

Fig. 6. Optimal volumes for different cell sizes and loading conditions for Material A

Fig. 7. Optimal volumes for different cell sizes and loading conditions for Material B

Fig. 8. Optimal volumes for different cell sizes and loading conditions for Material C

Fig. 9. Effect of material properties on the front membrane thickness when subjected to a vertical load of 20,000 N/m
3, \( t_1 \), \( t_2 \), and \( t_3 \) denote the optimal thicknesses for the front, back, and interior rigidified membranes, respectively, and \( v \) denotes the optimal volume for a 10 m long wall. We observe that buckling is an active constraint in all 54 design configurations evaluated in this study.

**Cell Size**

The relationship between cell size and optimal volume is depicted in Figs. 6–8 for Materials A, B, and C, respectively. For Materials A and B (Figs. 6 and 7), a cell size of 0.217 m results in the minimum volume for the 1,000 N/m load case, and a cell size of 0.433 m for the remaining two load cases. For Material C, cell sizes of 0.433 and 0.217 m yield similar minimum volumes. It is important to note that the variation in the optimal volumes is very small for the range of cell sizes investigated in this study. This property provides latitude to the designer in choosing a suitable cell size for a specific application.

There might, however, be relative advantages and disadvantages associated with smaller and larger cell sizes. When cells are relatively small, potential damage to a single cell would be less consequential to the overall structural integrity of the wall. At the same time, the fabrication process for a honeycomb-type RIS wall with a smaller cell size might be more complicated from a manufacturing perspective. Cell size also affects the optimal thicknesses of the front, back, and interior rigidified membranes. Table 3 shows that, as the cell size decreases, the optimal thicknesses of the rigidified membranes also decrease. We assume that a RIS wall with thinner membranes will generally be easier to store, and to inflate.

**Table 3.** Optimal Dimensional Parameters and Total Material Volumes for Materials A, B, and C

| Cell size \( s \) (m) | Vertical load \( (N/m) \) | Material A | | Material B | | Material C |
|------------------------|------------------------|------------|------------|------------|------------|
|                        | \( t_1 \) (mm) | \( t_2 \) (mm) | \( t_3 \) (mm) | \( v \) (m³) | \( t_1 \) (mm) | \( t_2 \) (mm) | \( t_3 \) (mm) | \( v \) (m³) | \( t_1 \) (mm) | \( t_2 \) (mm) | \( t_3 \) (mm) | \( v \) (m³) |
| 0.575                  | 1,000                  | 2.6        | 2.2        | 3.2        | 0.24        | 1.8        | 1.6        | 2.1        | 0.17        | 1.2        | 1.1        | 1.5        | 0.12        |
|                        | 10,000                 | 3.1        | 2.8        | 3.8        | 0.29        | 2.5        | 2.7        | 2.3        | 0.22        | 1.4        | 1.6        | 1.7        | 0.15        |
|                        | 20,000                 | 3.6        | 3.4        | 4.8        | 0.34        | 2.6        | 2.7        | 3.1        | 0.25        | 1.7        | 1.6        | 2.3        | 0.17        |
| 0.433                  | 1,000                  | 2.4        | 2.2        | 2.9        | 0.24        | 1.4        | 1.3        | 2.0        | 0.16        | 1.0        | 1.0        | 1.0        | 0.11        |
|                        | 10,000                 | 2.6        | 2.5        | 3.8        | 0.28        | 1.7        | 1.7        | 2.7        | 0.20        | 1.2        | 1.2        | 1.8        | 0.14        |
|                        | 20,000                 | 3.0        | 2.8        | 4.9        | 0.33        | 2.0        | 1.9        | 3.3        | 0.23        | 1.3        | 1.3        | 2.4        | 0.17        |
| 0.289                  | 1,000                  | 1.6        | 1.6        | 2.6        | 0.23        | 1.2        | 1.2        | 1.7        | 0.17        | 0.8        | 0.9        | 1.2        | 0.12        |
|                        | 10,000                 | 1.9        | 1.9        | 3.5        | 0.30        | 1.2        | 1.3        | 2.4        | 0.21        | 0.9        | 0.9        | 1.7        | 0.15        |
|                        | 20,000                 | 2.2        | 2.1        | 4.5        | 0.37        | 1.4        | 1.4        | 3.0        | 0.25        | 1.0        | 1.0        | 2.1        | 0.18        |
| 0.217                  | 1,000                  | 1.4        | 1.6        | 2.2        | 0.22        | 1.0        | 1.1        | 1.5        | 0.16        | 0.8        | 0.7        | 1.2        | 0.12        |
|                        | 10,000                 | 1.6        | 1.7        | 3.4        | 0.30        | 1.1        | 1.2        | 2.3        | 0.21        | 0.7        | 0.7        | 1.6        | 0.14        |
|                        | 20,000                 | 1.9        | 1.9        | 4.3        | 0.36        | 1.2        | 1.2        | 2.9        | 0.25        | 0.8        | 0.9        | 2.0        | 0.17        |
| 0.173                  | 1,000                  | 1.6        | 1.8        | 1.9        | 0.24        | 0.8        | 2.5        | 1.0        | 0.17        | 0.8        | 0.8        | 0.9        | 0.12        |
|                        | 10,000                 | 1.4        | 1.6        | 3.0        | 0.31        | 0.9        | 1.1        | 2.0        | 0.21        | 0.6        | 0.7        | 1.4        | 0.15        |
|                        | 20,000                 | 1.6        | 1.6        | 3.8        | 0.37        | 1.0        | 1.1        | 2.6        | 0.25        | 0.7        | 0.8        | 1.8        | 0.18        |
| 0.144                  | 1,000                  | 1.5        | 1.7        | 1.9        | 0.26        | 1.1        | 1.2        | 1.3        | 0.18        | 0.8        | 0.9        | 0.9        | 0.13        |
|                        | 10,000                 | 1.2        | 1.6        | 2.8        | 0.33        | 0.7        | 1.2        | 1.9        | 0.22        | 0.5        | 0.9        | 1.3        | 0.16        |
|                        | 20,000                 | 1.4        | 1.4        | 3.5        | 0.39        | 0.9        | 1.1        | 2.3        | 0.26        | 0.6        | 0.7        | 1.7        | 0.19        |
Material Properties

As can be anticipated, a stiffer material yields a leaner structural solution. This behavior can clearly be observed in Figs. 6–8. The stiffest material (Material C) results in the lowest optimal volume, followed by Material B and Material A. For Material C, the optimal volume of the wall is almost independent of the cell size. The optimal volumes of Materials B and C also have little dependence on the cell size.

Figs. 9–11 show the effect of the Young’s modulus ($E$) on the optimal thicknesses of the front, back, and interior rigidified membranes, respectively, for a vertical load of 20,000 N/m. As the Young’s modulus of the material increases, the resulting optimal thickness decreases for all three membranes. The results indicate that the optimal membrane thicknesses, and the optimal volumes, for Material A ($E=3$ GPa) are almost twice as much as those obtained for Material C ($E=30$ GPa).

Membrane Thickness

The optimal membrane thicknesses for the various design cases are provided in Table 3. The optimal thicknesses for the front, back, and interior membranes range approximately between 0.5 and 4 mm.

<table>
<thead>
<tr>
<th>Cell size $s$ (m)</th>
<th>Material A</th>
<th>Material B</th>
<th>Material C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_v$ (MPa)</td>
<td>$d_f$ (mm)</td>
<td>$d_i$ (mm)</td>
<td>$\sigma_v$ (MPa)</td>
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<tr>
<td>0.575</td>
<td>14.3</td>
<td>7.1</td>
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<tr>
<td>0.144</td>
<td>24.7</td>
<td>11.2</td>
<td>10.6</td>
</tr>
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</table>

Deflection

The upper limit on the deflection of the honeycomb-type RIS wall along the Y and Z directions is 0.025 m [1/120 times the height of the wall (3 m)]. Typical deflections for Materials A, B, and C for vertical load of 20,000 N/m are provided in Table 4. The deflections for the other load cases (1,000 and 10,000 N/m) are smaller than those reported in Table 4. We can also see that the maximum deflections measured along the Y and Z directions are significantly lower than the upper limit, making the deflection constraint inactive.

Induced Stress

The von Mises stress induced in the honeycomb-type RIS wall is constrained to be less than the yield strength of the material. The yield strengths of Materials A, B, and C are provided in Table 1. Typical von Mises stresses induced in the wall for the three materials, under a vertical load of 20,000 N/m, are provided in Table 4. For the cell sizes investigated, the maximum von Mises stress induced in the honeycomb-type RIS wall does not exceed the yield strengths of the respective materials. The maximum stresses experienced by Materials B and C are significantly lower than their yield strengths. However, for Material A and a cell size of 0.144 m, the maximum von Mises stress is very close to its yield strength. The higher stresses and larger optimal membrane thicknesses may make Material A less desirable. Fig. 12 depicts the von Mises stress contours on the front membrane of a
honeycomb-type RIS wall using Material C, a cell size of 0.433 m, and under the action of a vertical load of 20,000 N/m.

Buckling

Results indicate that buckling is an active constraint upon optimization. Local buckling dominates the structural behavior of the honeycomb-type RIS wall systems. Initial analysis revealed that local buckling is prominent near the bottom edge of the wall, as shown in Fig. 5. The optimization tends to increase the overall thickness of these membranes to avoid this local buckling behavior. This results in membrane thickness values that exceed the upper limit of 5 mm. As stated earlier, thick membranes are less practical from deployment and fabrication perspectives. To lessen the risk of failure due to buckling, we placed an additional plate of 5 mm thickness in that region, as indicated in Fig. 5. The additional supporting plates can be placed in series, to cover the entire bottom edge of the honeycomb-type RIS wall. The assembly can be mechanically attached to the foundation system of the housing, after which the honeycomb-type RIS wall can be inserted, inflated, and rigidified.

Comparison between Honeycomb-Type and Rectilinear-type RIS Wall Systems

In this section, the results of the honeycomb-type RIS wall systems are compared to those of the rectilinear-type RIS wall systems that were studied previously (Van Dessel et al. 2003b). Fig. 13 illustrates the rectilinear-type RIS wall system. Similar material properties, loading scenarios, and design constraints were considered during the study of both systems. Table 5 provides a comparison of the optimal results between the honeycomb-type and rectilinear-type RIS wall systems. The quantities \( v_{\text{min}} \) and \( v_{\text{max}} \) denote the range of possible optimal volumes for the different structural configurations considered. It is seen that, for the conditions and cases investigated, the rectilinear-type RIS system is considerably more efficient compared to the honeycomb-type RIS system in terms of material volume. We also note that the difference in material usage becomes more pronounced with increasing vertical load and material stiffness. For Material A \( (E=3 \text{ GPa}) \) and a vertical load of 1,000 N/m, the honeycomb-type RIS wall uses approximately 30% more material compared to the rectilinear-type wall system. For Material C \( (E=30 \text{ GPa}) \) and a vertical load of 20,000 N/m, the honeycomb-type RIS wall uses approximately 70% more material compared to that of the rectilinear-type wall system. Also, the von Mises stresses generated in the honeycomb-type RIS wall system are higher compared to those generated in the rectilinear-type RIS wall system. From this perspective, the rectilinear-type RIS systems represent a more efficient design.

We note, however, that the performance of the rectilinear-type RIS wall system is greatly affected by bay size. That is, material usage changes significantly with small changes in bay size. In contrast, the honeycomb-type RIS wall system does not appear to be very sensitive to the cell size. Optimal volumes for various cell sizes differ only marginally. While not evaluated in this paper, we expect that the honeycomb-type RIS wall system will possess better in-plane shear resistance compared to that of the rectilinear-type RIS wall system. Finally, the honeycomb-cell structure will introduce a redundancy in the wall. Damage to a single honeycomb cell does not necessarily imply structural failure to the entire wall, making it possibly more robust to local damage. Hence, the honeycomb-type RIS wall might be preferred over the rectilinear-type RIS wall system in those instances where (1) resistance to in-plane shear is important; (2) relatively small vertical loads are applied; (3) a lower modulus material is desired; and (4) robustness is desirable.

The two systems show the following similarities in their behavior: (1) Buckling is the active constraint upon optimization of both systems. More specifically, local buckling governs the thickness of the membranes. (2) For both systems, Material C yields the smallest thickness values, which are desirable for the deployment of the RIS wall. (3) The deflections of the wall along the Y and Z directions are small for both systems.

Conclusions

In this study, we have examined the feasibility and merits of honeycomb-type RIS structures. In particular, we have determined optimal dimensional parameters for various honeycomb-type RIS wall systems. The optimization results indicate that the amount of material needed to satisfy the design criteria is not significantly affected by the size of the hexagonal cells. The optimal structural designs for the honeycomb-type RIS wall systems
of different cell sizes use approximately the same amount of material. This property allows the designer to select a cell size with considerable freedom. It is also observed that the optimal membrane thickness decreases with decreasing cell size. We have further compared the performance of various honeycomb-type RIS wall systems with that of various rectilinear-type RIS wall systems. It was found that honeycomb-type wall systems require significantly more material to satisfy similar design criteria and loading conditions, but may yet be desirable in certain cases.

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### Notation

The following symbols are used in this paper:

- $b$ = buckling load factor;
- $d_{\text{max}}$ = maximum allowable deflection;
- $d_Y$ = deflection along $Y$ direction (vertical);
- $d_Z$ = deflection along $Z$ direction (out of plane);
- $E$ = modulus of elasticity;
- $s$ = honeycomb cell size;
- $t_{\text{min}}$ = minimum allowable membrane thickness;
- $t_{\text{max}}$ = maximum allowable membrane thickness;
- $t_1$ = thickness of front membrane;
- $t_2$ = thickness of back membrane;
- $t_3$ = thickness of interior membranes;
- $v$ = material volume;
- $\sigma_v$ = von Mises stress; and
- $\sigma_y$ = yield strength.

### References


