COMBINING NUMERICAL ANALYSIS AND ENGINEERING JUDGMENT TO DESIGN DEPLOYABLE STRUCTURES

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Abstract—Deployable structures are prefabricated space frames that can be stored and transported in a compact folded configuration and then deployed rapidly into a load bearing configuration. The structures are stable and stress-free in the folded and the deployed configuration, but exhibit a highly nonlinear behavior during deployment. Therefore, their design process should include simulation of their response in two phases: in the deployed configuration under service loads, and during deployment. The first phase involves linear analysis while the second one requires a geometrically nonlinear finite element formulation. Both simulations can be very demanding in terms of computer storage requirements as the number of degrees of freedom increases. In addition, the nonlinear analysis is quite expensive because of the large number of load steps that are necessary in order to trace the complete load-displacement path. This paper first describes a set of numerical models that were used to simulate the exact structural behavior using the finite element program ADINA. Then, some simplified analytical and numerical models are proposed that can be applied in the preliminary design stage, or even for final design, in order to obtain approximate but satisfactory results at a much lower cost.

1. INTRODUCTION

Prefabricated, transportable and reusable structures can be a very promising alternative for applications for which speed and ease of erection are of particular importance. They can be used for example as temporary emergency shelters after natural disasters, or for storage of equipment and accommodation of personnel at remote construction sites. They can also be the only solution in situations of limited availability of transportation space as is the case with aerospace applications.

During the last years a research project at the Massachusetts Institute of Technology has investigated a new type of prefabricated, mobile space frames called deployable structures [1]. An example is the dome shown in Fig. 1. Like previously proposed deployable structures, these structures consist of straight bars connected in pairs by pivotal connections forming so called scissor-like-elements. These elements are the basic building modules that are assembled together to make up large structures. The innovation of this new type lies in the fact that special geometric constraints among the lengths of the bars are enforced so that the structures are stable and stress-free in both the folded and the deployed configuration. Thus, problems of previous designs that needed external stabilization or had members with residual stresses are avoided. The advantages associated with this behavior and the details of the geometric design are described in [1–3] and have been demonstrated through the construction of a series of physical models [4], like the one illustrated in Fig. 2.

Although the two limiting configurations are stress-free, geometric incompatibilities cause the occurrence of second order strains and stresses in the members during the deployment process. In that stage the structural behavior is characterized by geometric nonlinearities and a snap-through that 'locks' the structure and makes it stable in the deployed configuration [5, 6]. This response during deployment has to be taken into account in the design process in order to avoid very high deployment loads that would make the feasibility of deployment questionable, and to achieve a linear elastic material behavior in the deployment phase so that the load bearing capacity in the deployed configuration is not jeopardized.

Therefore, the design of deployable structures must be done in two phases. First, the response in the deployed configuration under service loads has to be predicted. Then, the deployment process of the structure must be simulated. Of course, these two phases are interdependent, therefore, the overall design process is an effort to find a compromise between desired stiffness in the deployed configuration, and desired flexibility during deployment.

Because of the complicated geometry of deployable structures and their pivotal connections that allow large relative rotations between members, it is not possible to obtain an analytical solution for either the linear analysis in the deployed configuration, or the nonlinear deployment analysis. As explained in [5], the finite element package ADINA [7, 8] has been used for the numerical modeling of the problem. The final details of this modeling will be presented as part of this paper. The sophisticated hardware and software requirements, and the high cost of the analysis, motivated us to seek simpler, approximate models that can be used for preliminary design or even final
Fig. 1. The folded, the deployed, and an intermediate configuration of a spherical dome.
design, in cases of limited hardware availability or budget restrictions. These models will also be described and their results compared to the more exact numerical models.

2. ANALYSIS IN THE DEPLOYED CONFIGURATION

The analysis of deployable structures in the deployed configuration is relatively straightforward since the behavior is linearly elastic. There are three possible failure modes: strength, stiffness and buckling. Strength failure can be defined as the occurrence of stresses that are higher than a predefined maximum allowable stress in an 'allowable stress' approach to the problem, or as an overall bearing capacity failure in an ultimate strength design environment. Stiffness failure is associated with deflections larger than a given limit depending on the shape of the structure and the application for which it is used. Both of these failure modes can be investigated with a simple linear analysis. Figure 3 shows the original and deformed configuration of a simply

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Fig. 2(a)–(c)—Caption overleaf.
Fig. 2. A physical model of a shallow deployable dome.
supported square flat slab subjected to a vertical uniformly distributed load. Only one-fourth of the slab has been analyzed because of symmetry considerations. Standard two-node isoparametric beam elements [9] have been used to model the members.

A linearized buckling analysis [9] gives very accurate results for the buckling modes and the critical buckling loads of the same structure. This has been verified by comparing the results to those of a geometrically nonlinear analysis. The accuracy of a linearized buckling analysis for this problem was expected because the pre-buckling behavior is characterized by small displacements. Figure 4 shows the fundamental buckling mode of such a slab. Out-of-plane buckling of some of the scissor-like-elements in a symmetrical fashion can be observed. It is interesting to mention that the fundamental buckling mode is symmetrical for square slabs with odd number of square units in the two directions, and anti-symmetrical for slabs with even number of units.

From a design perspective it is interesting to determine which of these three potential failure modes is critical. Figure 5 attempts to provide an answer to this question, by comparing the maximum failure loads associated with the above three modes as a function of the number of units in each direction, keeping the size and properties of units the same for all slabs. The results illustrated in this figure cannot
be easily generalized. However, it is fair to say that strength and buckling are more critical for smaller number of units, while stiffness is almost always the deciding factor for larger numbers of units that are associated with longer spans. As mentioned above, the exact finite element analysis in the deployed configuration is not particularly expensive, since it is linear. But the storage space requirements are large, and start becoming a problem as the number of units increases. This is also due to the complicated pivotal and hinged connections that require more than one nodal point to describe them.

This provided the motivation for the derivation of an equivalent continuum model that predicts the deflections of flat deployable slabs in the deployed configuration under vertical loads. This transformation was carried out in two steps, first by substituting 'equivalent' uniform beams for all scissor-like-elements, and then using an available model [10] to substitute a uniform slab for the result-

![Fig. 6. Accuracy of equivalent continuum model.](image)

ing grid of uniform beams. Although the final approximate model is analytical, it was obtained through computational modeling, since the transformation of scissor-like-elements to uniform beams involves application of the direct stiffness method within a symbolic manipulation program such as MACSYMA [11]. More details about this derivation will be reported in a paper that is currently in preparation.

The approximate model can predict only deflections, but this is what is needed because stiffness

![Fig. 7. Comparison of numerical and experimental results for deployment analysis.](image)
governs the design for a large number of units, which is the case when the computer space requirements make finite element analysis prohibitive. The accuracy of the deflections predicted by the equivalent continuum model is illustrated in Fig. 6 for square slabs as a function of the number of units in the two directions. Again, the results are very accurate only for large number of units, but it is then that use of this model is meaningful anyway.

3. ANALYSIS DURING DEPLOYMENT

The simulation of the deployment process within ADINA has been accomplished by using a large displacements-small strains lagrangian formulation [9], and modeling the members with a series of two-node isoparametric beam elements. The automatic load incrementation algorithm [12] has been used in order to follow the complete load-displacement curve. The influence of initial geometric imperfections and discrete joint sizes has been taken into account [13]. The effect of friction was incorporated into the finite element model by using pairs of nonlinear translational springs at all pivotal connections. The forces of these springs represent the frictional moment that resists relative rotation of the two bars that constitute each scissor-like element. The numerical results obtained in this

![Fig. 8. Successive deformed configurations of a multi-unit flat slab.](image-url)
manner were in excellent agreement with test results as illustrated in Fig. 7 for a structure consisting of a single unit.

Next, deployment analysis of multi-unit structures was attempted [14]. Figure 8 shows successive stages of the dismantling process for a flat slab consisting of nine square units in a three by three layout. Figures 9 and 10 illustrate the variation of the required dismantling load and maximum stress respectively, as a function of the in-plane displacement of a corner node towards the center of the slab during folding. The load of Fig. 9 is one of the eight concentrated in-plane loads applied on the eight corner nodes of the slab in a radial direction in order to achieve dismantling.

The results of this analysis were very satisfactory, and provided the necessary information for the design of the slab. The problem however, was the high cost. This particular analysis was carried out on a CRAY-2 supercomputer, and the execution time was 4477 CPU seconds (approximately one hour and fifteen minutes). Running this problem on a smaller computer that might be accessible to a practicing engineer would require several days. But even if such a powerful computer is available the cost of the analysis is prohibitive, especially if we take into account that the design would be an iterative process and would therefore require several similar analyses.

A way to overcome these problems is to use the results of the analysis of a single-unit structure and try to predict the corresponding results for multi-unit structures. Of course, the boundary conditions imposed for the analysis of the simple structure should try to simulate those of a unit of a multi-unit assemblage. Then, the stresses were expected to be comparable. This expectation was verified as illustrated in Fig. 11 which compares axial stresses at a given cross-section of a given member in the single-unit structure, and the corresponding member in a three by three unit slab. In addition, the required dismantling load for the large $3 \times 3$ unit structure turned out to be three times the one for the single unit as shown in Fig. 12. In fact, this result can be
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Fig. 12. Comparison of load–displacement curves for 1 and 3 × 3 units.

The accuracy of this expression is very high as illustrated by Fig. 13 that compares predicted and exact maximum loads and Fig. 14 that compares predicted and exact load variations near the limit point for several unit configurations. Therefore, results of the deployment analysis of single units can definitely be used for the prediction of corresponding quantities for many units not only for preliminary design, but also, if necessary, for final design.

4. CONCLUSIONS

Some useful general conclusions can be drawn from this study. Deployable structures offer a nice example of a design problem for which numerical analysis is absolutely necessary. It would have been impossible to gain such insight into the structural behavior of these structures and actually formulate design guidelines without the powerful hardware and software tools that are available today. We believe that the use of computers and numerical analysis capabilities as design tools in everyday engineering practice will emerge as a very strong trend in the near future, as increased computational capabilities become accessible to more engineers at affordable prices.

At the same time, this paper demonstrates how engineering judgment is still, and will always be, necessary for the effective use of those tools. No matter how powerful computational equipment one has at his/her disposal, one should keep in mind that the cost and the effort for analysis and design can be significantly reduced by thinking in advance about the basic engineering concepts that govern the structural behavior, and taking advantage of these concepts to simplify the numerical model, without necessarily sacrificing the accuracy of the results.
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