DESIGN AND ANALYSIS OF ORTHOGONALLY COMPLIANT FEATURES FOR DURAFORM/SLS MANUFACTURED PLATES

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Abstract

In many applications of parts manufactured by Solid Freeform Fabrication (SFF), compliance is an important factor. In order to achieve given deformation goals with optimal shape, the design of compliant mechanisms and elements fabricated with SFF techniques must take into account the particular constraints and boundary conditions of the target application as well as the specific material properties of the part. The present work focuses on the design and evaluation of compliant features for a geometrically constrained thin-wall part subject to loads normal to its tangent plane. Such features would need to be embedded in the object. The manufacture of prosthetic sockets for lower-limb amputees is the specific application presented, where greater compliance is needed at sites in contact with pressure sensitive tissues. Sample parts were fabricated by selective laser sintering, and the material used was Duraform.

1 Introduction

Compliance is in many cases a fundamental and desired property of a mechanical structure. In many applications, compliance is very important for proper function of a part. In others it is a much more elegant and functional design solution that substitutes joints and links of mechanisms by incorporating controlled flexibility within the structure itself. In order to proceed with the design of compliant features, very strict constraints must be considered and evaluated [Howell, 2001]. The part material and its mechanical properties must be studied, boundary conditions for the structure must be well defined, the target deformation under specific loads must be set, and a thorough failure prevention study, using both static and fatigue theory, should be performed.

This article focuses on the primary design stages of orthogonally compliant features of plates and thin walls (where the load/displacement direction of the feature is normal to the plate or wall), and evaluating the design options that are more promising for a given set of design goals for an specific application. The design example to be considered is the incorporation of compliance features in sockets for below-the-knee prostheses, produced with selective laser sintering (SLS) using Duraform.

2 Fabrication of Sockets for Below-the-Knee Prostheses using SLS

The production of sockets for prostheses using SFF (Figure 1) has several potential advantages compared to common, more labor intensive and time-consuming fabrication methods [Walsh et al., 1989; Freeman et al., 1998]. One of the main advantages is that SFF directly creates sockets from digital shape information, eliminating the need for molds, hand lamination and finishing procedures. Another advantage of SLS is the ability to create complex geometries with minimal cost penalty in manufacturing, which significantly expands the options for developing and exploring alternate socket designs.

Figure 1: On the left and center, a patient testing an SLS fabricated socket; on the right, the description of the parts of a prosthesis for below-the-knee amputees.

Our method, developed through collaboration of the Laboratory for Freeform Fabrication at The University of Texas at Austin and the Rehabilitation Engineering Laboratory of The University of Texas Health Science Center at San Antonio [Rogers et al., 2001], creates a computer model of the socket from digital source taken from the patient's residual limb. The shape of the socket is designed so that the load is supported by specific regions of the limb that can safely resist contact pressures generated when the patient walks. This design is called the Patellar-Tendon Bearing (PTB) socket, illustrated schematically in Figure 2.

Some areas of the residual limb are not suitable for high contact pressures, either because they are too sensitive to pain, are susceptible to developing sores, or other various health issues. Notwithstanding the reason, high pressures at these sites lead to discomfort for the patient during gait (thus affecting rehabilitation) and, sometimes, pose a health risk for the patient. Thus, it is necessary to incorporate means of relieving contact pressure over these areas. One way to achieve this is to make the socket orthogonally compliant at these high pressure contact sites.

Currently, local compliance is achieved by reducing the wall thickness of the socket at pressure sensitive areas, as seen in Figure 3. However, this approach provides limited compliance and pressure relief. A more effective design may be to take advantage of the ability of SLS to easily create geometric variants of traditional socket shapes that allows a controlled expansion of socket volume to adapt to limb change during gait.

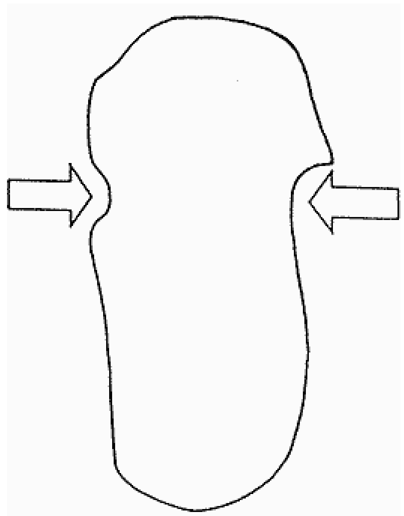

Figure 2: Schematic of a socket based on the PTB approach, with main force vectors shown.

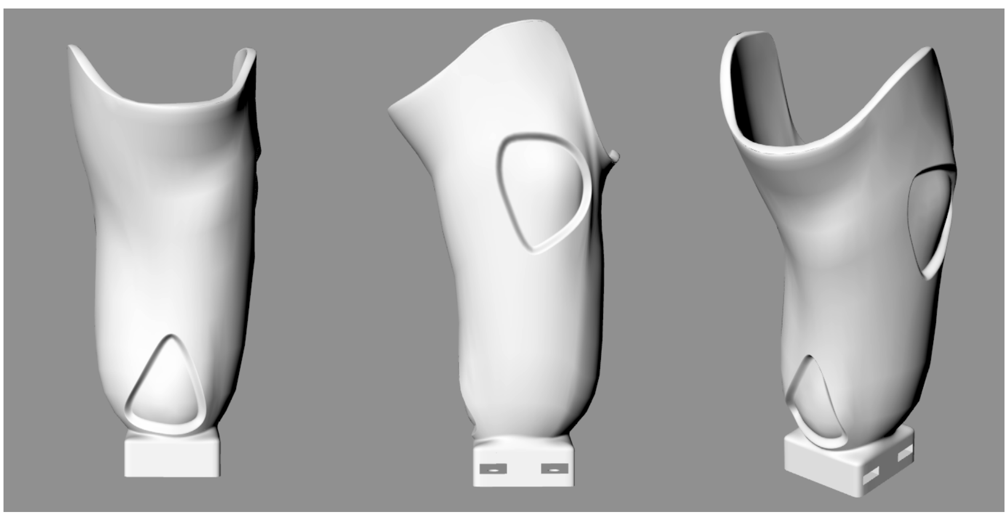

Figure 3: Example of a current SLS fabricated socket with locally thinned walls in areas where compliance is needed.

3 Design Goals and Constraints

In order to allow the effective and successful design of orthogonally compliant features to be incorporated into the socket structure, it is necessary to identify the design goals and constraints. First, a target deformation for the compliant region when subjected to the normal steady-load pressure must be specified. The optimum value of the desired displacement at the center of the compliant site is, however, difficult to set precisely, since it depends on several parameters that may vary from patient to patient and can be highly subjective. Our experience has shown that positive results occur when the target displacement should be between 2 and 4 mm.

Second, the incorporated compliant features on the wall of sockets should not compromise structural safety during gait. Moreover, such features should not affect the shape of the inside of the socket and should have minimal impact on its outer appearance. The latter condition, although very subjective, is nevertheless important for the patient to feel positive about using the prosthesis.

Third, areas with no material on the socket wall, such as slots and holes, should have minimal dimensions. Since the limb requires a constant minimal pressure to be applied to all areas, even on more sensitive areas, large holes on the wall should be avoided altogether. Features that lead to high localized contact pressure gradients and concentrations should also be avoided, since they can lead to circulatory problems for the patient.

Finally, compliant features should not produce spikes or sharp corners when deformed. Hence, slots on the socket wall should not self-intersect or cross each other. Figure 4 shows an example of a possible socket with compliant features that satisfy these design goals and constraints.

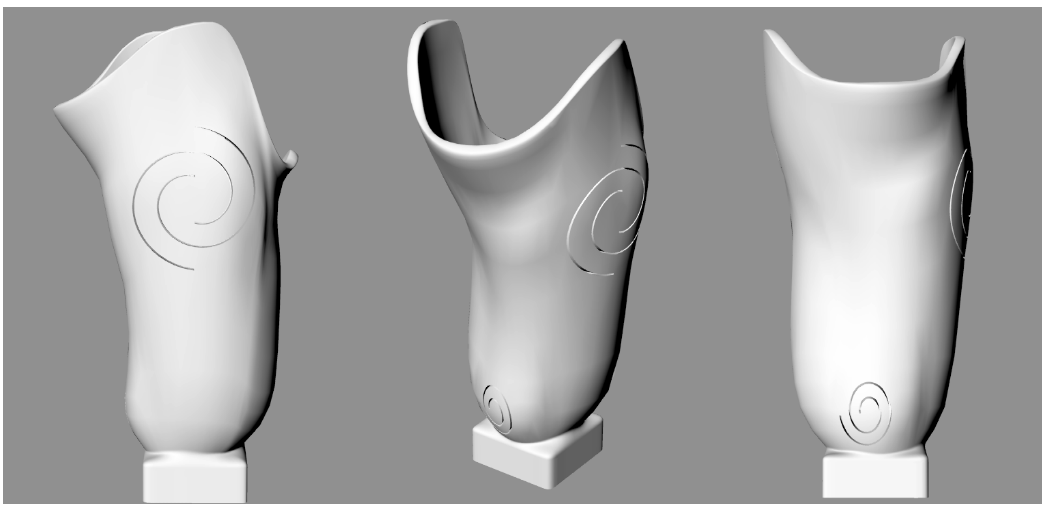

Figure 4: Example of orthogonally compliant features incorporated in a socket.

4 FEM Evaluation of Some Design Options

For the evaluation of various design options that satisfy the design constraints described in the previous section, computer modeled test discs were evaluated using finite element analysis (FEA) and prototypes were produced with SLS and Duraform material. These discs were dimensionally similar to compliant areas on the socket, as shown in Figure 5. Geometric features such as slots and holes will be added to each disc to assess their ability to provide compliance.

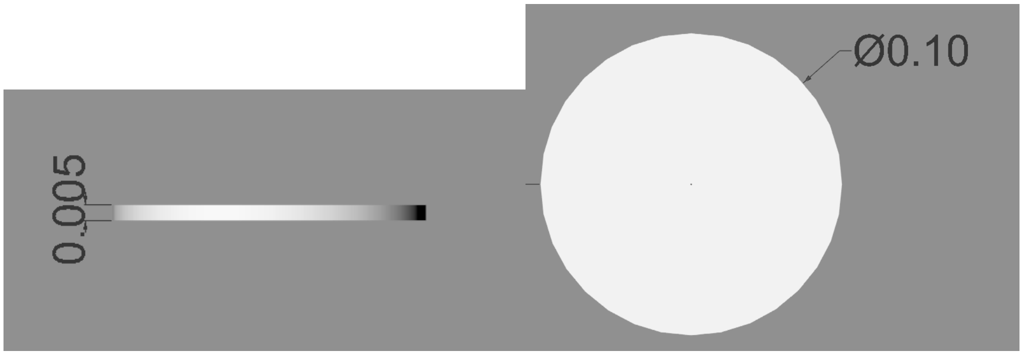

Figure 5: Test disc to evaluate compliance options (dimensions in meters)

The boundary conditions for the FEA analysis where defined as follows: the borders of the discs were fully restrained and a pressure of 10 kPa is applied at one of the free faces. SDRC I-DEAS 8 was used for the analysis and all elements were defined as 10-node parabolic tetrahedra. The material properties used for Duraform were those published by 3D Systems (Valencia, CA).

Figure 6 shows the deformation results for a solid control disc, with no compliant features. The displacement at the center due to the 10 kPa pressure was 5.54×10^{-5} m. Figures 7, 8 and 9 show the results for 4, 8 and 16 straight slots radially distributed on the discs, respectively. The central displacement achieved varied from 6.27×10^{-5} to 7.20×10^{-5}m as the number of straight slots was increased. However, a design with more than 16 slots would start to compromise structural integrity due to higher stress concentrations.

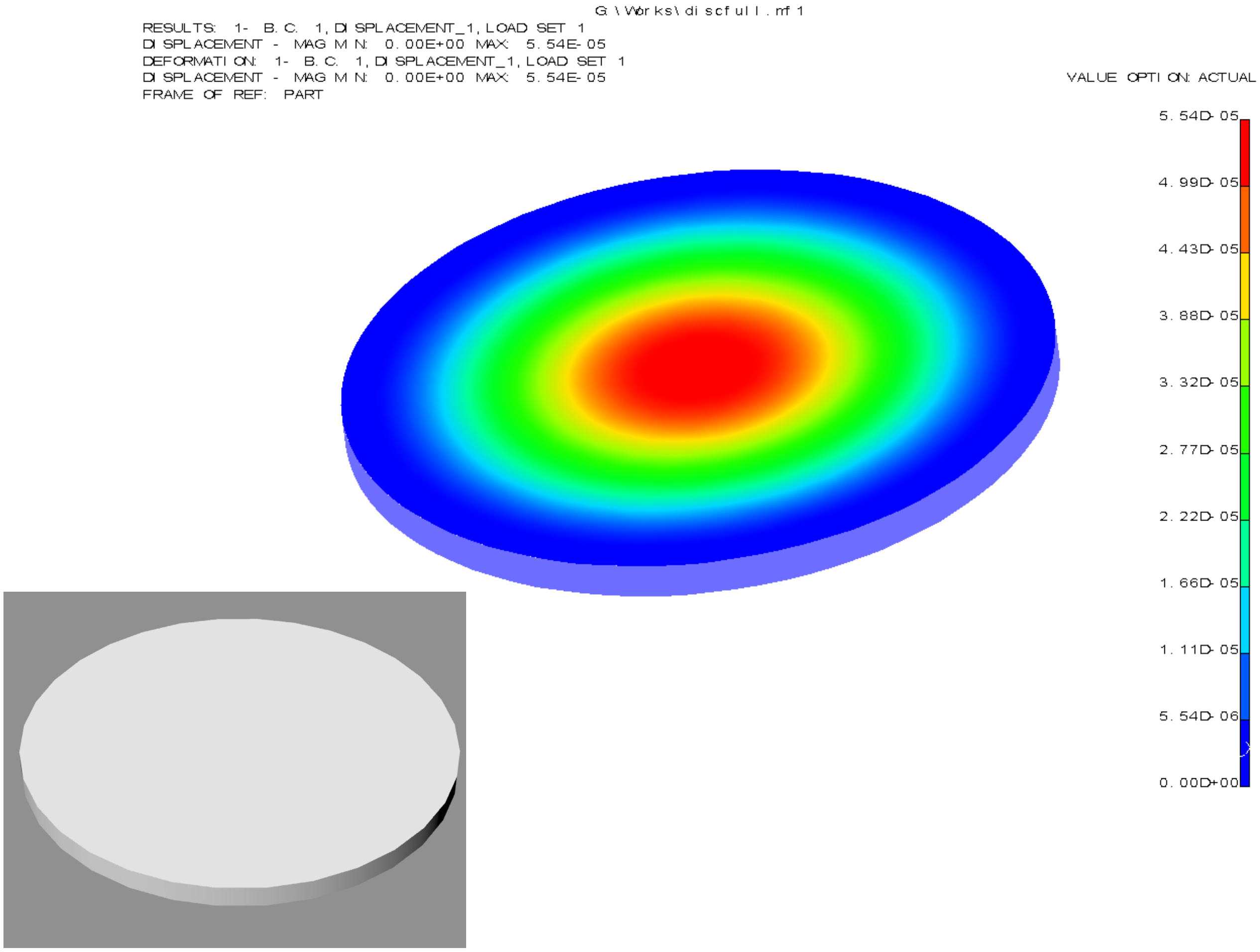

Figure 6: FEA deformation results for control disc with no special compliant features.

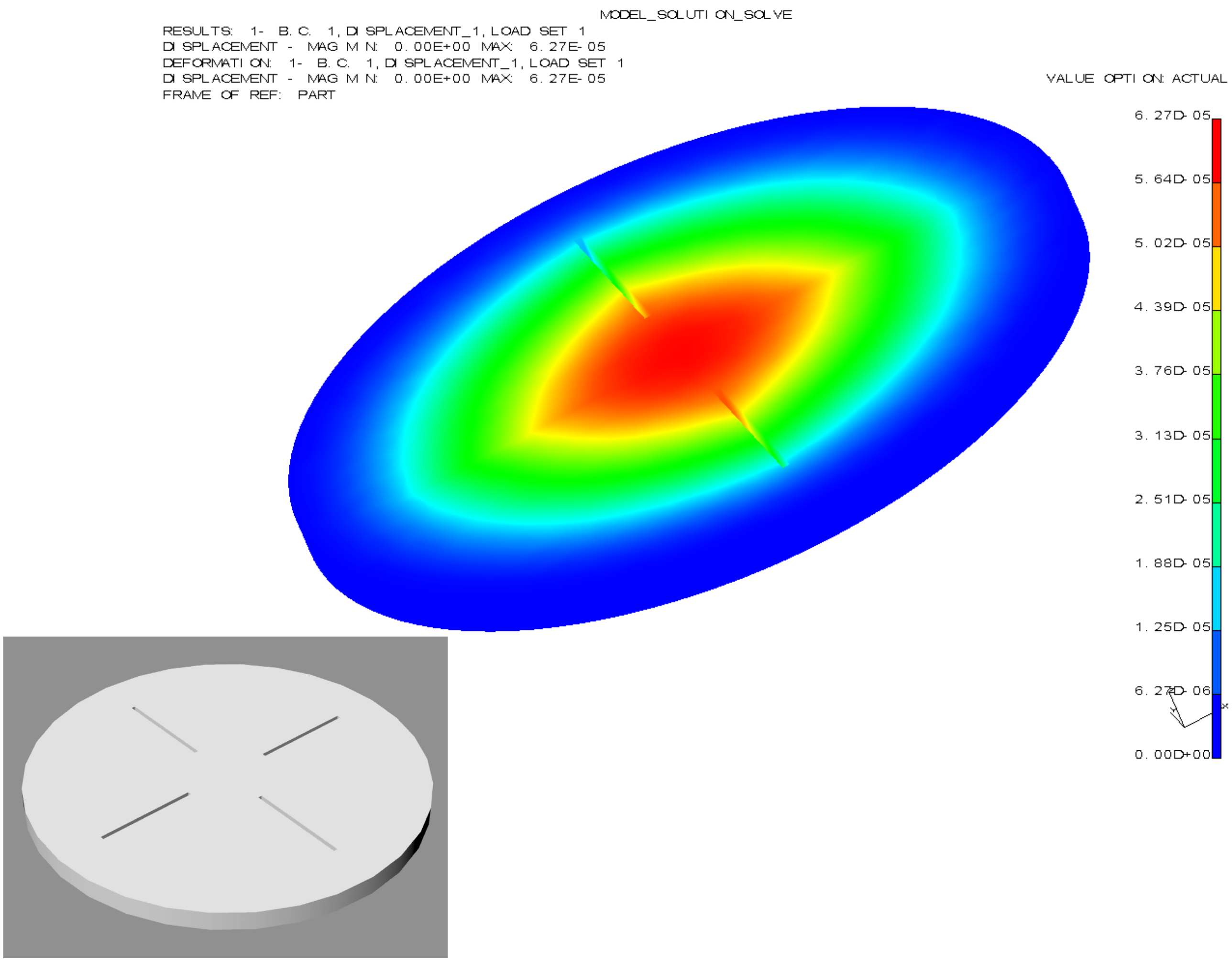

Figure 7: FEA deformation results for test disc with 4 radial slots.

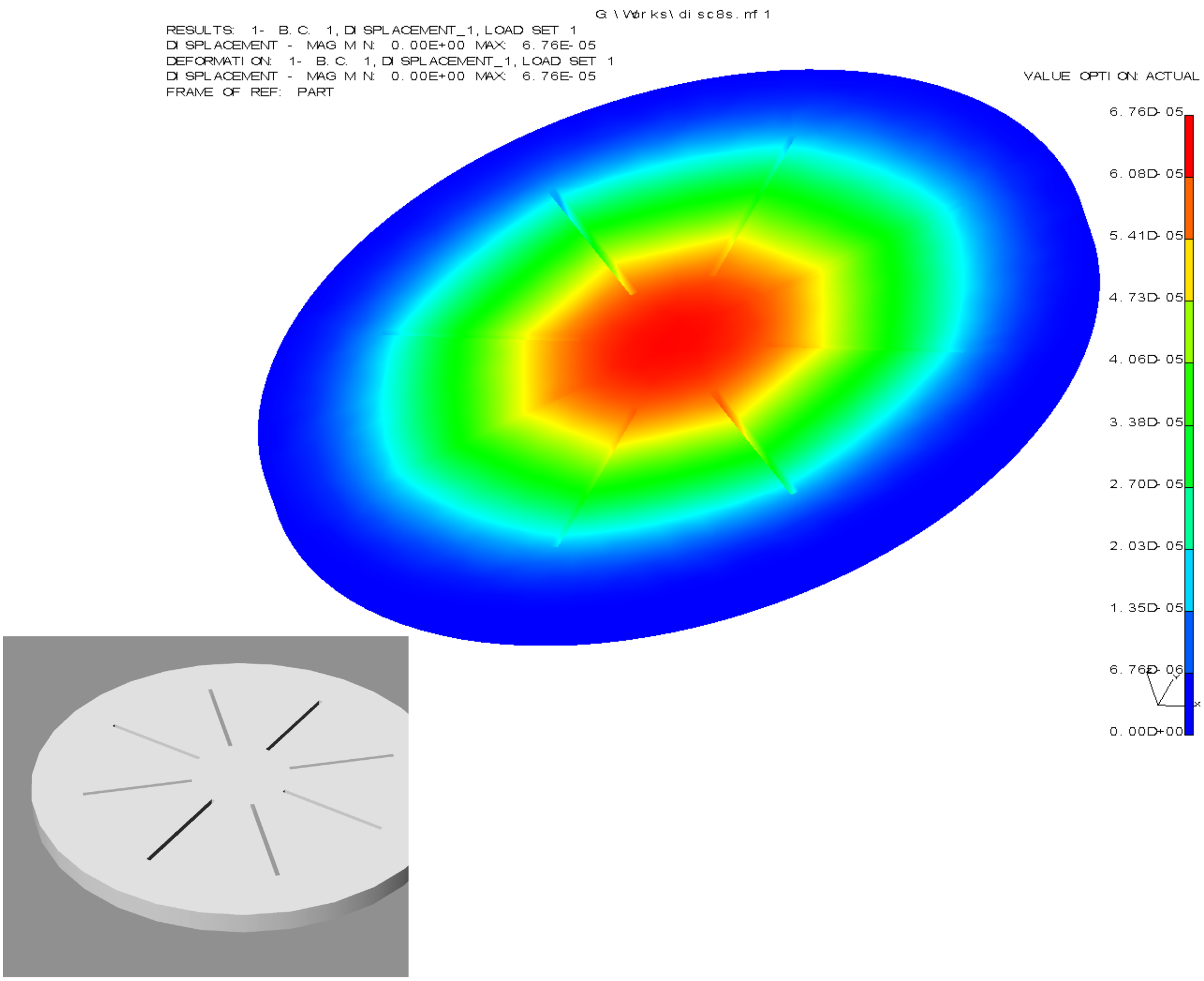

Figure 8: FEA deformation results for test disc with 8 radial slots.

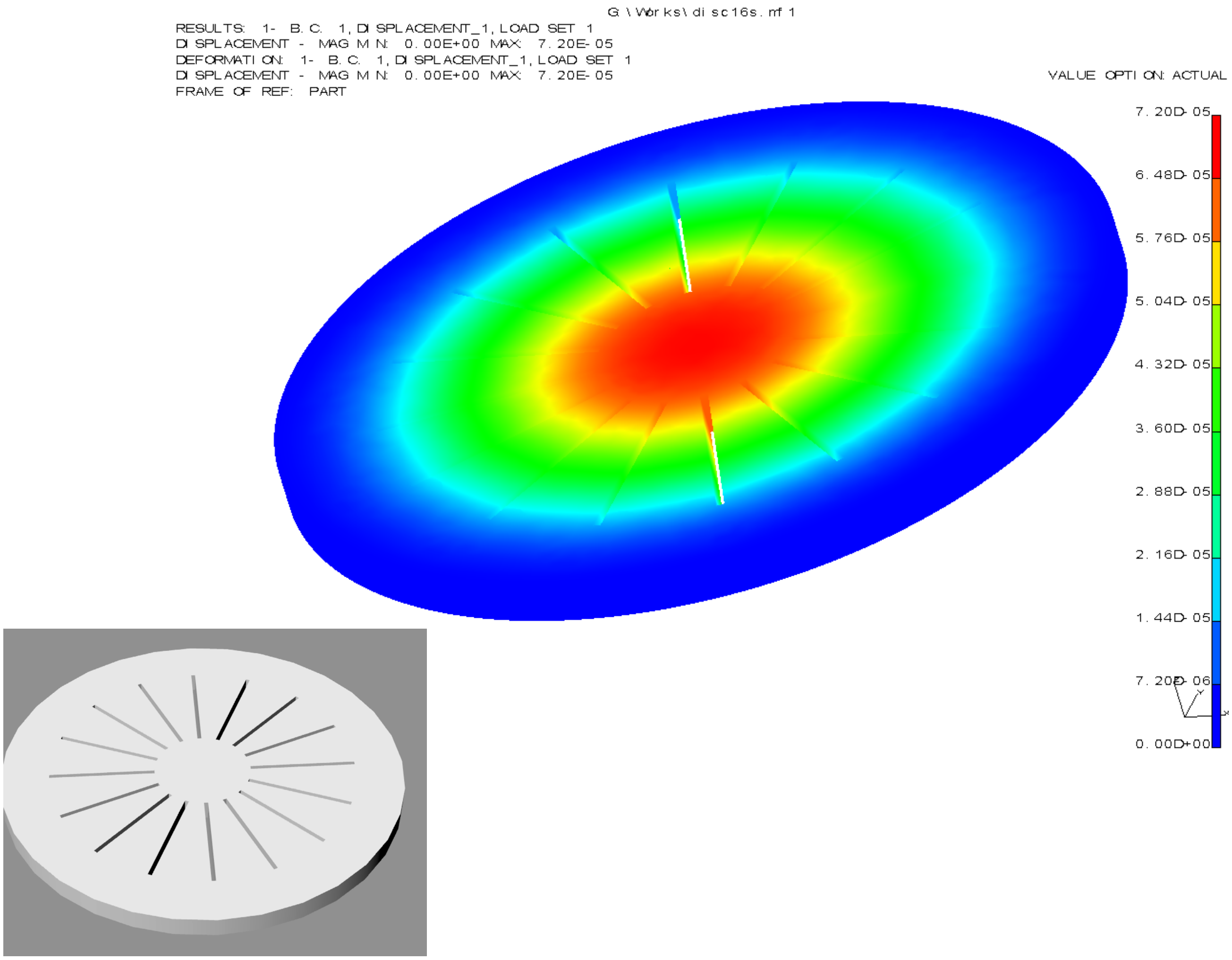

Figure 9: FEA deformation results for test disc with 16 radial slots.

Figure 10 presents an option with 4 larger void spaces, which is topologically similar to the solution given by optimization methods. For this design, the central displacement reaches a value of 8.52 x 10^{-5}m, which is still not as high as desired. In addition, there is a potential problem with localized pressure gradients (due to contact discontinuity) at the borders of the holes that may affect the peripheral circulation in the residual limb.

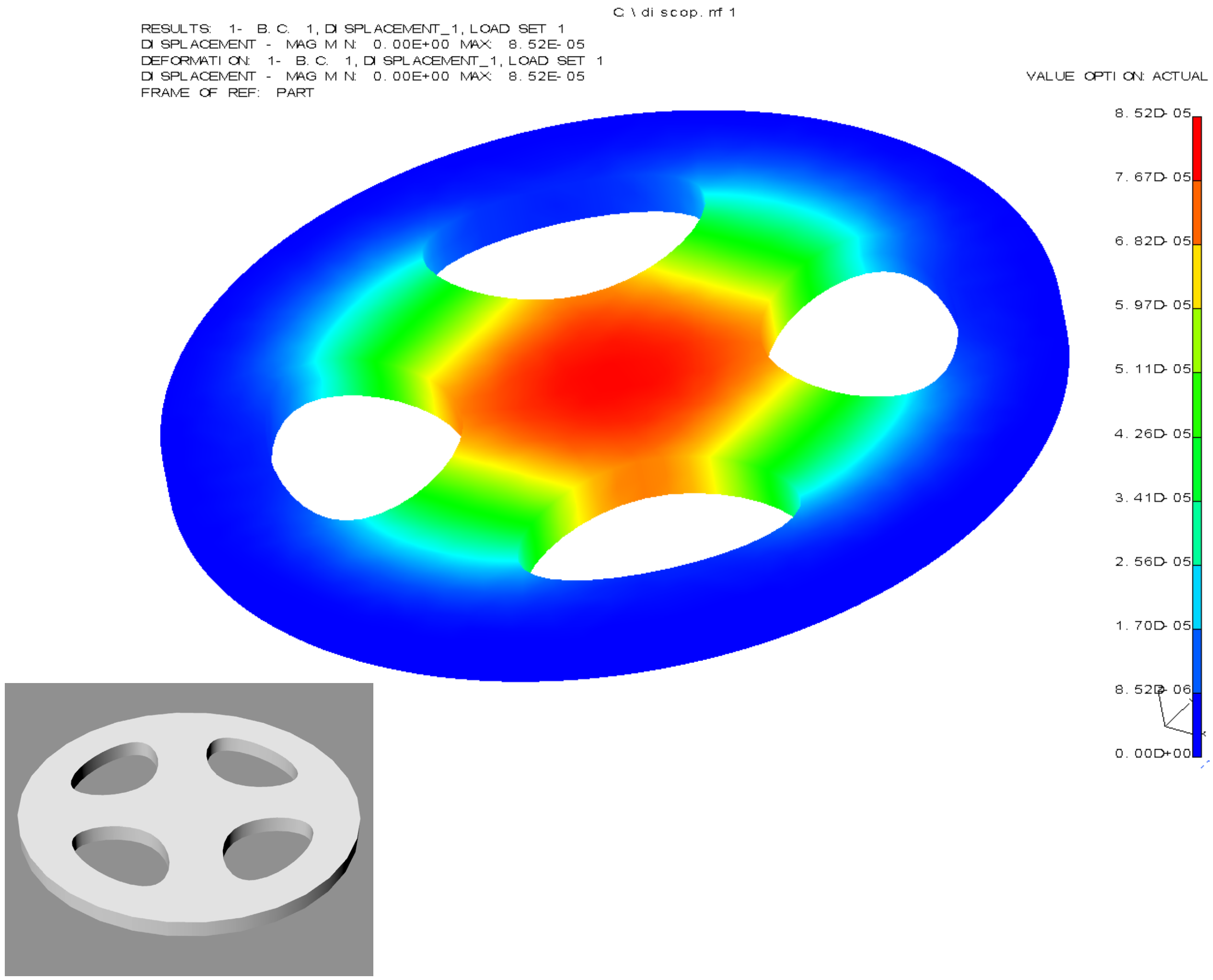

Figure 10: FEA deformation results for test disc with 4 void spaces.

Finally, Figures 11 and 12 display the results for designs with spiral slots (2 and 4 radially distributed spirals, respectively). For the case with 2 spirals, a central displacement of 4.38 x 10^{-3} m was achieved, which is very satisfactory. The case with 4 spirals, on the other hand, results in a central displacement of 8.88 x 10^{-3} m, which was considered to be too large.

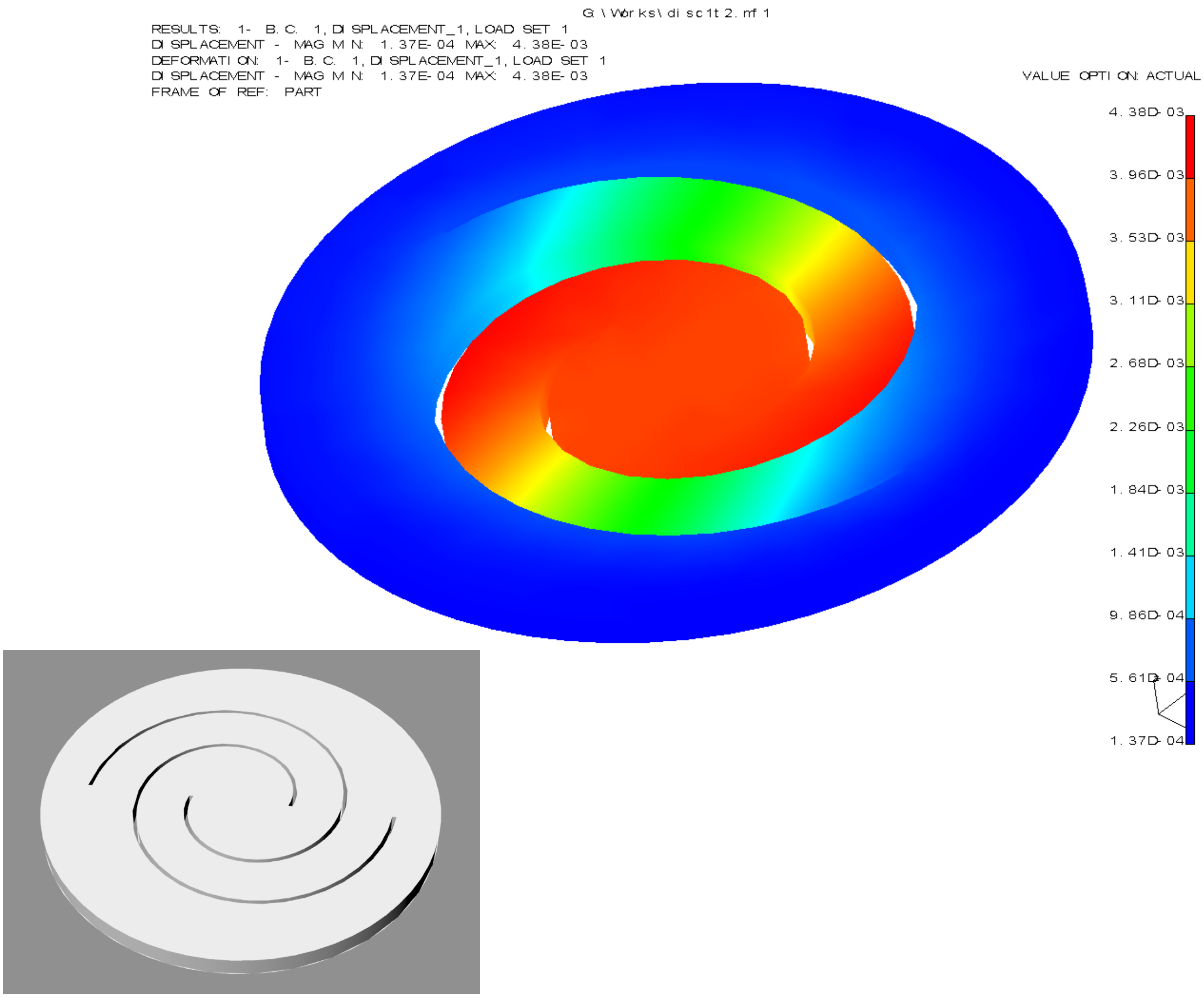

Figure 11: FEA deformation results for test disc with 2 spiral slots.

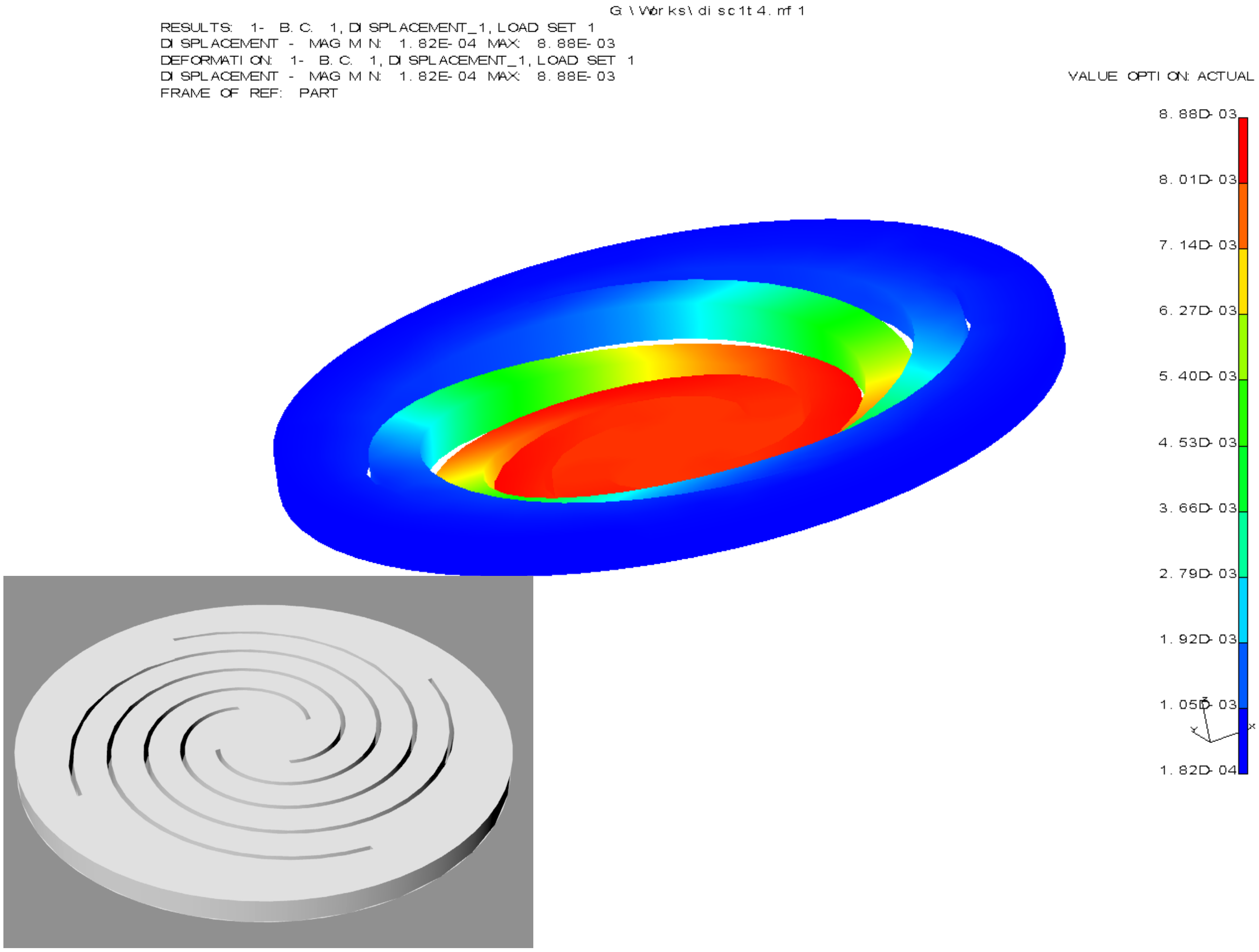

Figure 12: FEA deformation results for test disc with 4 spiral slots.

5 Conclusions and Future Work

This article presents a preliminary evaluation of design options for orthogonally compliant features to be used in sockets for below-knee prostheses using SLS. Of the options investigated, the most effective design incorporated two spiral slots, which balanced providing the needed displacement while avoiding high contact pressures.

This work is a preliminary study of specific topologies for compliant features using a trial and error approach. Future work will be directed at applying a modified version of topology optimization method to systematically optimize designs that satisfy the design constraints. One such technique is the Homogenization Method [Bendoe et al., 1993; Suziki and Kikuchi, 1991; Nishiwaki et al., 1998], which considers a design domain described by a 2D microstructure of unit cells, each one with void space (with sides defined by values **a** and **b**, which vary from 0 – no material – to 1) and orientation (defined by angle θ) (Figure 13). In general terms, the method consists of a recursive approach that calculates homogenized elasticity coefficients for the design domain, calculates sensitivities with FEM, optimizes for compliance with respect to **a** and **b**, filters results to eliminate checkboard patterns, updates angle θ and repeats all steps until convergence is achieved.

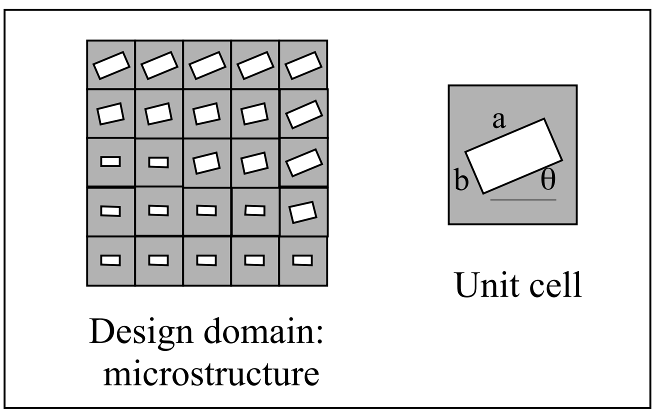

Figure 13: Design domain for the Homogenization Method.

However, some modifications must be applied to this method to allow its use with orthogonally compliant plates. First, a microstructure with orthogonal boundary conditions must be developed. Another fundamental modification is to filter solutions with large void areas, which violate design constraints for socket application. Finally, fatigue analysis should be performed on the compliant features.

Acknowledgements

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