Solution of Inverse Problem of Elastic-Plastic Deformation using Isight and Abaqus

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Abstract: As a rule, compression spring shapes are designed to conform to the required compression force using general theories. Under some conditions, lateral forces on the springs can be an issue. Lateral forces are greatly affected by contact conditions between springs and structures and the spring's self-contact. Numerical calculations to determine the spring shape must take these factors into consideration. However, the manufacturing method causes a high degree of plastic deformation by a process called "prestressing" which means that the final shape of the spring is different from the coiled metal piece required for manufacturing. So even if a shape with small lateral force is derived by calculations, the original shape of the spring before prestressing must be determined from that shape.

The authors propose an iterative method for solving this problem. The method estimates a reasonable candidate for the original shape and refines that shape using the results of repeated elastic-plastic analyses. An automated system integrating each process with Isight and Abaqus was designed. Although it is generally difficult to change the shape of a part in Abaqus, an analysis template was developed and made the automation of this procedure possible.

Keywords: Spring, Inverse Problem, Analysis Automation, Plastic Deformation

1. Introduction

Lateral force can be a problem for compression springs in some products. Lateral force is largely affected by the contact of the ends of a spring with part faces or contacts between parts of the spring wire. To maintain a low lateral force, these factors must be taken into account and the spring shape must be optimized. FEM analysis can ascertain spring shapes that have a small lateral force. But compression springs are usually compressed in a process called prestressing, which causes a high degree of non-linear plastic deformation. In order to manufacture a spring with small lateral force, the coiled metal shape prior to prestressing must be determined. In this study, the solution used to determine that shape will be reported. The solution was achieved by integrating Isight and Abaqus.

2. Procedure

The following terms have been defined.

- Prestressed Shape: A shape with small lateral force that has gone through the prestressing process.
- Original Shape: A coiled metal shape needed to manufacture the Prestressed Shape.
- Optimized Original Shape: The target of the iterative method, used to manufacture the prestressed shape.
- Assumed Original Shape: An approximation used in the prestressing analysis to determine the Optimized Original Shape.
- Prestressing Analysis: The analysis that replicates the plastic deformation of the prestressing process.
- Prestressing Results: Results from the prestressing analyses, which are compared to the Prestressed Shape to determine if an analysis has converged.

The three steps taken to inversely solve this problem are as follows. The schematic diagram of the solution is shown in Figure 1.

1. Determine Assumed Original Shape
    - An approximation of the Original Shape is determined using several criterion to be shown later.
2. Modify Assumed Original Shape
    - A Prestressing Analysis is executed on the Assumed Original Shape. A Prestressing Result is produced.
    - The difference between the coordinates of each node of the Prestressing Result and those of the Prestressed Shape are calculated.
    - The Assumed Original Shape is modified by adding the calculated differences in the coordinates to the Assumed Original Shape.
3. Repeat of Modification
    - The modification process is repeated until the Assumed Original Shape converges and is optimized. Convergence is considered complete when the difference between the Prestressing Results and the Prestressed Shape are within the tolerances of the Prestressed Shape.

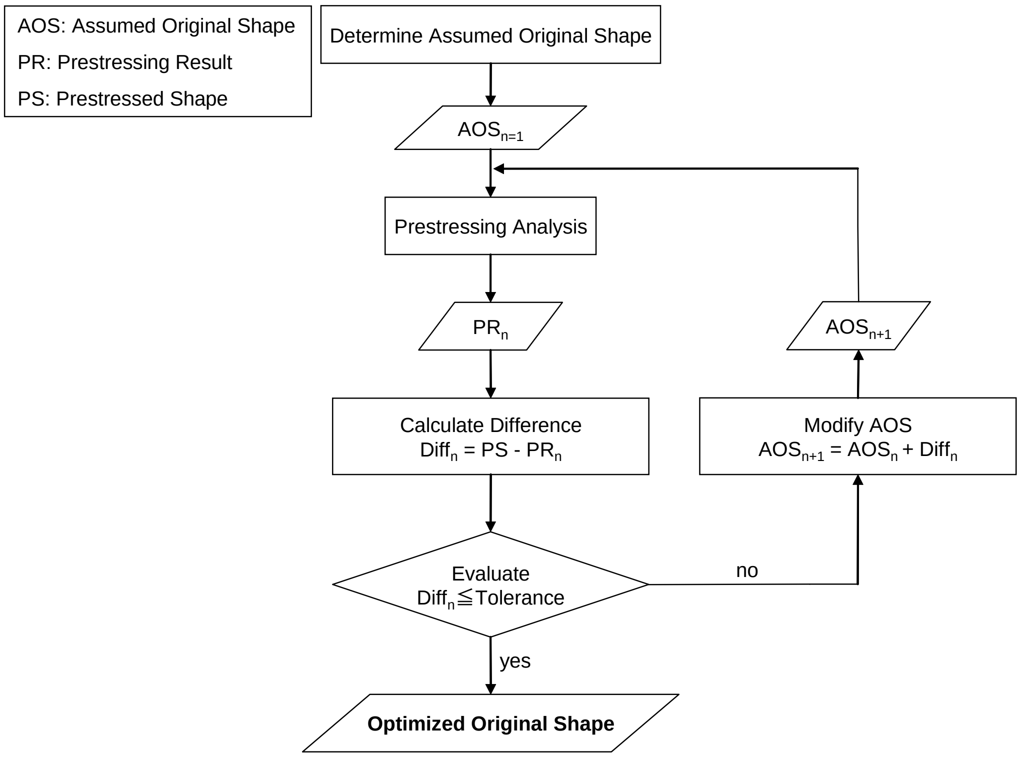


Figure 1. Schematic Diagram of Inverse Problem Solution

3. Isight Setup

The procedure was automated using Isight. Figure 2 shows the Isight Simflow created for this inverse problem solving.

- The initial setup of Isight was stored in “Settings”
- Prestressing Analysis was executed in “Abaqus”.
- Customized Abaqus python scripts, “Scripts”, were used to automate calculation of the differences between the Prestressing Results and the Prestressed Shape and modify the Assumed Original Shape.

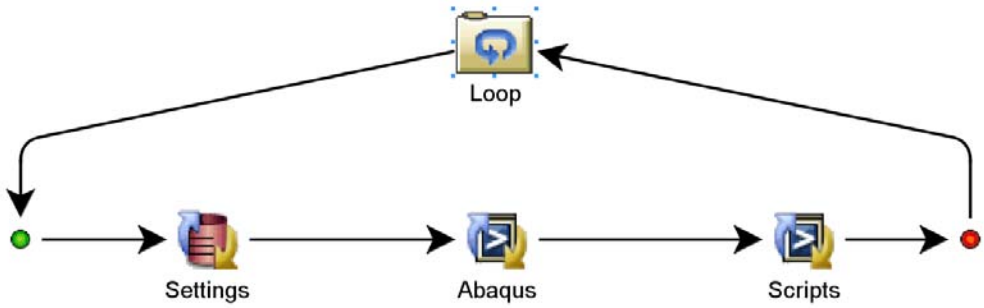
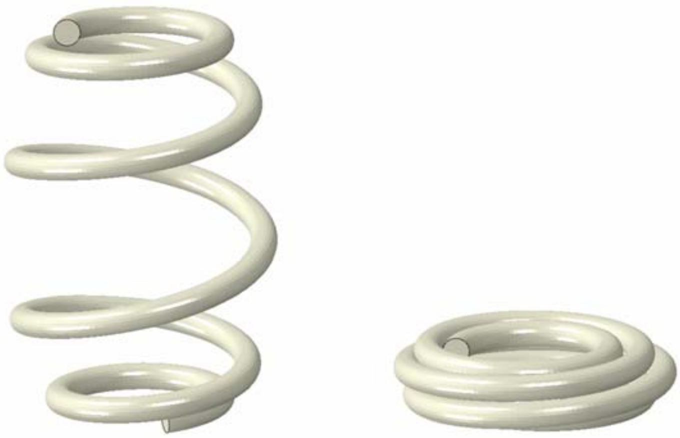


Figure 2. Isight Simflow

4. Validation of Prestressing Analysis

4.1 Prestressed Shape

The Prestressed Shape is a barrel-shaped spring (Figure 3). This shape allows the smaller end coils to be compressed inside the larger ones providing a long spring stroke with a large compression force in a limited space. At maximum compression, contact occurs between spring coils.



(Max Diameter ≅ 110mm, Uncompressed Length ≅ 190mm)

Figure 3. Prestressed Shape

(Left: Uncompressed, Right: Maximum Compression)

4.2 Procedure

In the analysis model (Figure 4), the Original Shape is placed between two rigid plates and the bottom rigid plate is restrained in space (Figure 4 (a)). The spring is compressed with the plates to a prescribed displacement (Figure 4 (b)). After deformation, compression is removed (Figure 4 (c)). The material elastic-plastic property was derived from a tensile test of the standard material used for the spring (Figure 5). C3D8R solid element was used for the analysis model. This analysis was performed using Abaqus/Standard (*Dynamic).

4.3 Results (Precision of the Prestressing Analysis)

The deformation of the spring by prestressing is shown in Figure. 4. The plastic deformation in the longitudinal direction caused a shrinkage of 25 mm and the error between the experimental results and the analysis was 1.3mm. The precision of the Prestressing Analysis used in this study can be defined as approximately 5 %.

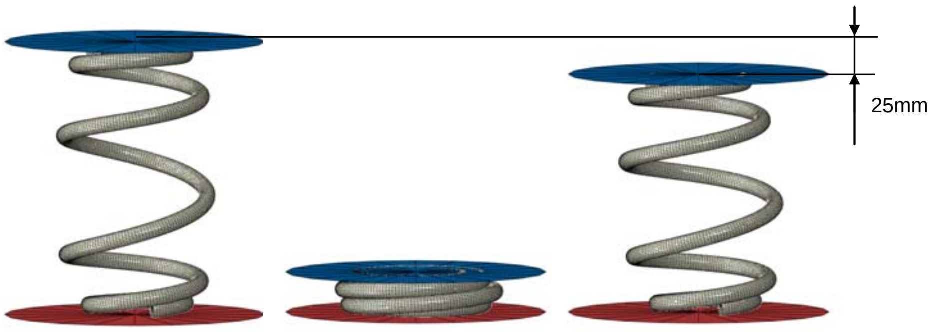


Figure 4. Prestressing Analysis Procedure.

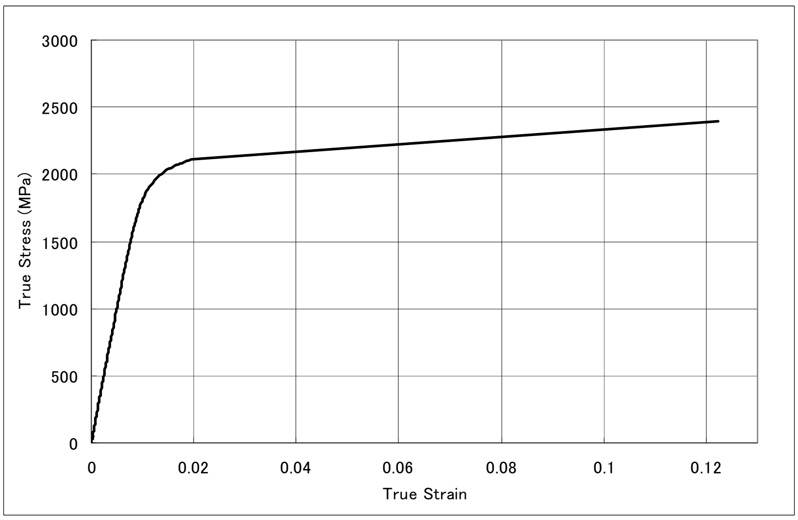


Figure 5. True Stress-Strain Curve derived by Material Tensile Test.

5. Analyses of Inverse Problem

5.1 Parameters

There is a possibility that the Assumed Original Shapes will affect convergence. Therefore three Assumed Original Shapes were prepared to compare convergence. The analysis series were defined as “AOS I”, “AOS II” and “AOS III”.

1. Assumed Original Shape I

   The Prestressed Shape was uniformly lengthened by 25mm in total. 25mm is approximately equal to the total difference between the Prestressed Shape and the Original Shape.

2. Assumed Original Shape II

   The Prestressed Shape was uniformly lengthened 10mm in total.

3. Assumed Original Shape III

   The plastic deformation caused by prestressing the Original Shape was assumed to be nearly identical to the plastic deformation caused by using analysis to prestress the Prestressed Shape a second time. The Assumed Original Shape was generated as follows.

   - Prestressing was applied to the Prestressed Shape by analysis to determine the shape of the spring that was prestressed twice.
   - The difference between the coordinates of each node of the twice prestressed spring and the Prestressed Shape were calculated.
   - The calculated differences between the coordinates were added to the Prestressed Shape to make Assumed Original Shape III.

5.2 Result

Analyses to detect the Original Shape were performed on each of the three Assumed Original Shapes. Figures 6, 7 and 8 show the iterations leading to the convergence of the Prestressed Shape. In these graphs, the horizontal lines show the number of coils and the vertical line shows the difference between each coordinate of the Prestressing Results and the Prestressed Shape (Figure1, $Diff_n$).

In AOS I, analysis showed that the first iteration of the Prestressing Results was quite different from the Prestressed Shape (Figure 6). Failure to consider the distributional plastic deformation in the Prestressed Shape is the most reasonable explanation.

The first iteration of the Prestressing Results in AOS II was also quite different from the Prestressed Shape (Figure7), but closer than that of the Prestressing Results of AOS I.

The first iteration of the Prestressing Results of AOS III was much closer initially and gradually and smoothly converged to the Prestressed Shape (Figure 8). From this analysis we can deduce that Assumed Original Shape III will correspond closely to the Original Shape.

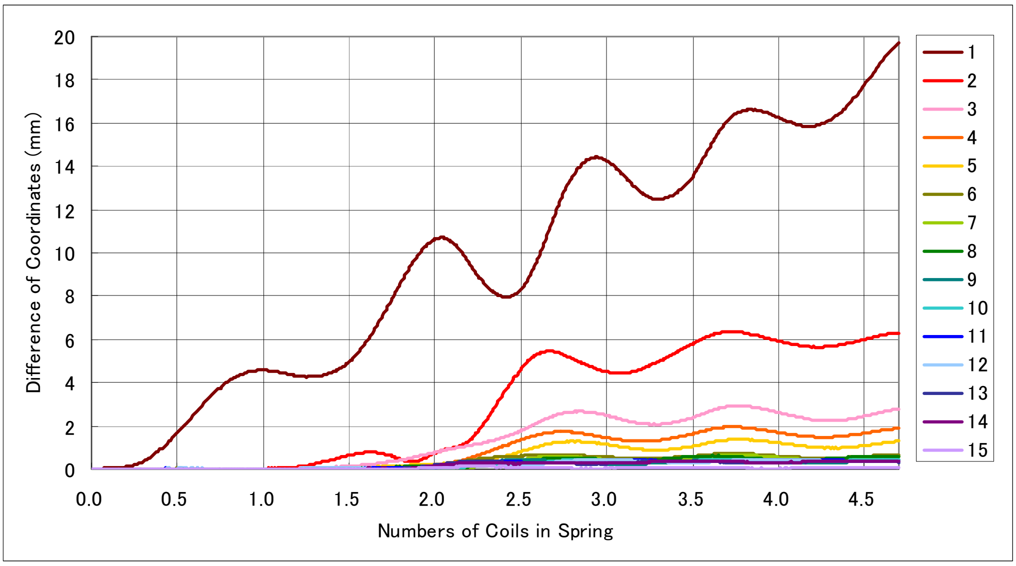


Figure 6. Convergence of Prestressing Results Using Assumed Original Shape I.

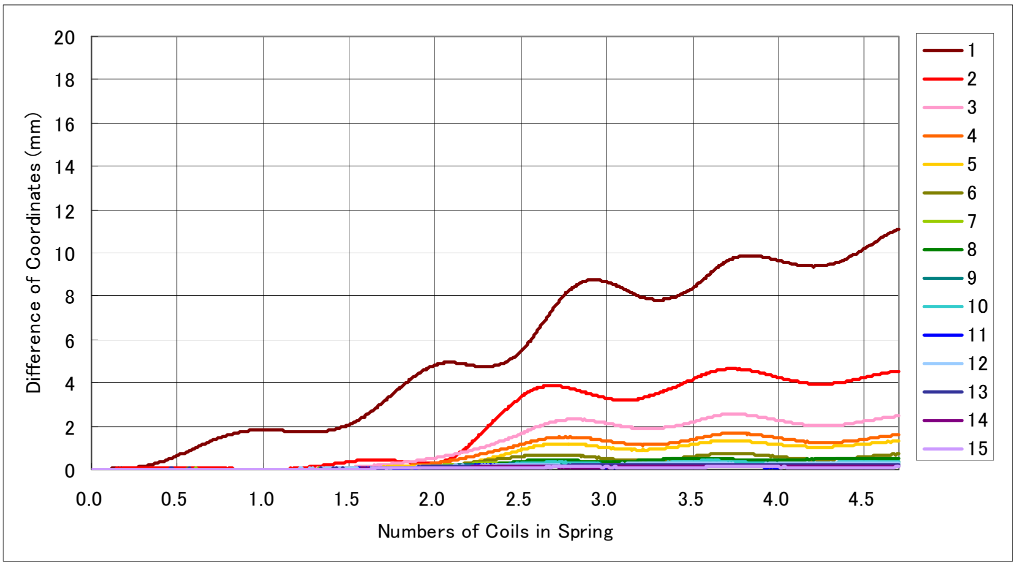


Figure 7. Convergence of Prestressing Results Using Assumed Original Shape II.

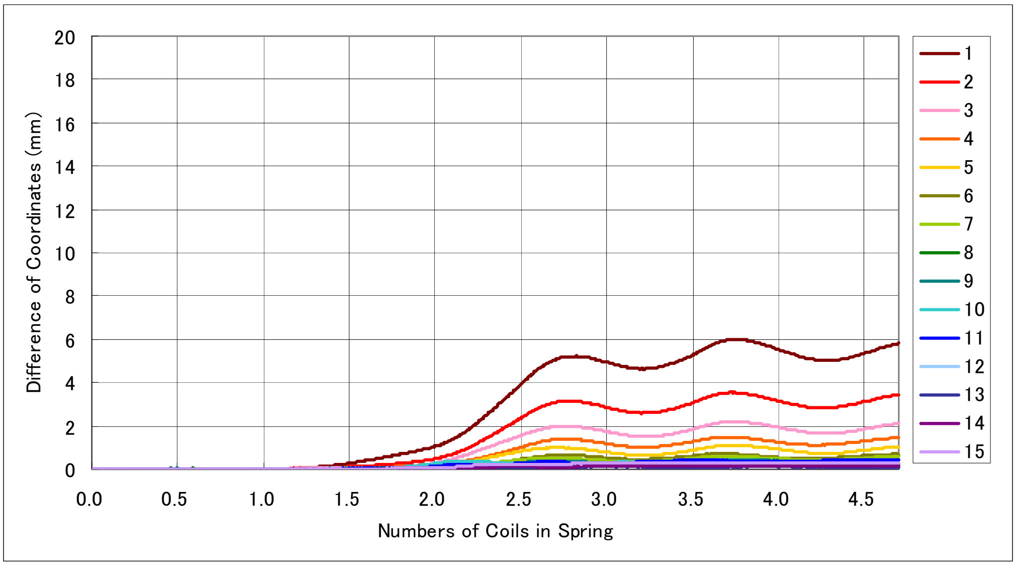


Figure 8. Convergence of Prestressing Results Using Assumed Original Shape III.

5.3 Comparison of AOS I, II and III

In Figure 9, the horizontal line shows the number of iterations and the vertical line shows the maximum differences between coordinates in each iteration. The Assumed Original Shape affected the convergence in the first iteration but after three iterations there was little difference. The maximum difference between the Prestressing Results and the Prestressed Shape is approximately 0.1mm. This means that although the analyses compared the final iteration of the Prestressed Results with the Prestressed Shape, the Assumed Original Shape had only a minor effect on convergence. Therefore, the proposed solution is a reasonable method for determining the Original Shape in inverse problems which have significant plastic deformation.

In Figure 10, the horizontal lines shows the number of coils and the vertical line shows the difference between each coordinate of the Prestressing Results iterations and the Prestressed Shape. To compare the convergence to the Prestressed Shape, three iterations of each of the three Prestressing Results are shown. Iterations 5 and 10 and the iteration in which the Prestressing Results and the Prestressed Shape converged were chosen. The point at which the maximum differences occurred between the Prestressing Results and the Prestressed Shape varied, but the amount of the difference was very consistent.

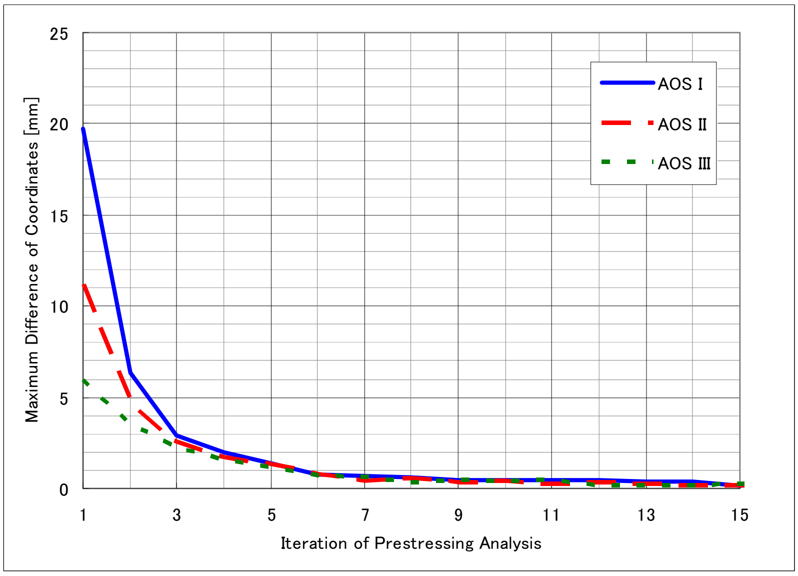


Figure 9. Comparison of Convergence in AOS I, II and III.

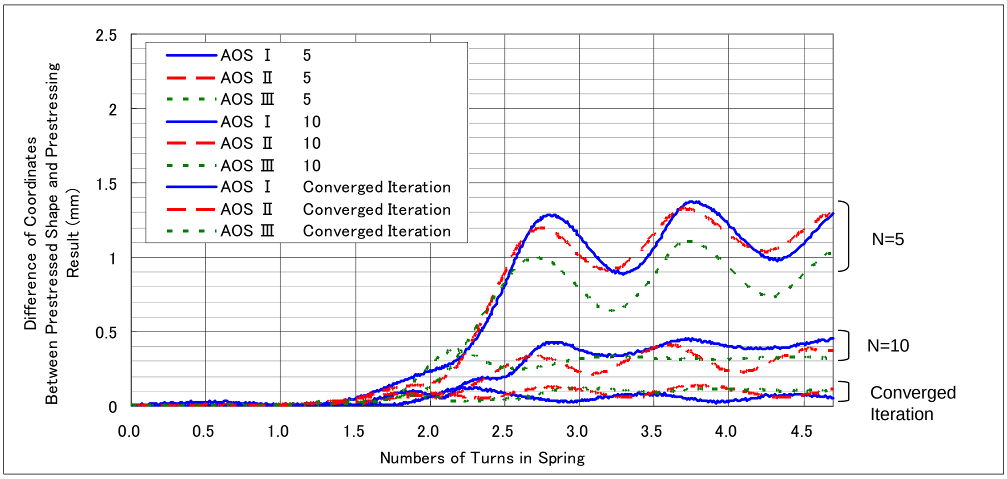


Figure 10. Comparison of Iterations in AOS I, II and III.

5.4 Validation of Proposed Solution

In this section, the convergence of the Optimized Original Shape with the measured original shape will be explained to validate the proposed solution.

In Figure 11, the horizontal line shows the numbers of coils and the vertical line shows the differences between each coordinate of the Original Shape and the Optimized Original Shape that was determined by the proposed solution. The maximum difference between the Optimized Original Shape and the Original Shape was 1.8mm. Furthermore, it was confirmed that if the Prestressing Results are same, the Original Shapes are also the same.

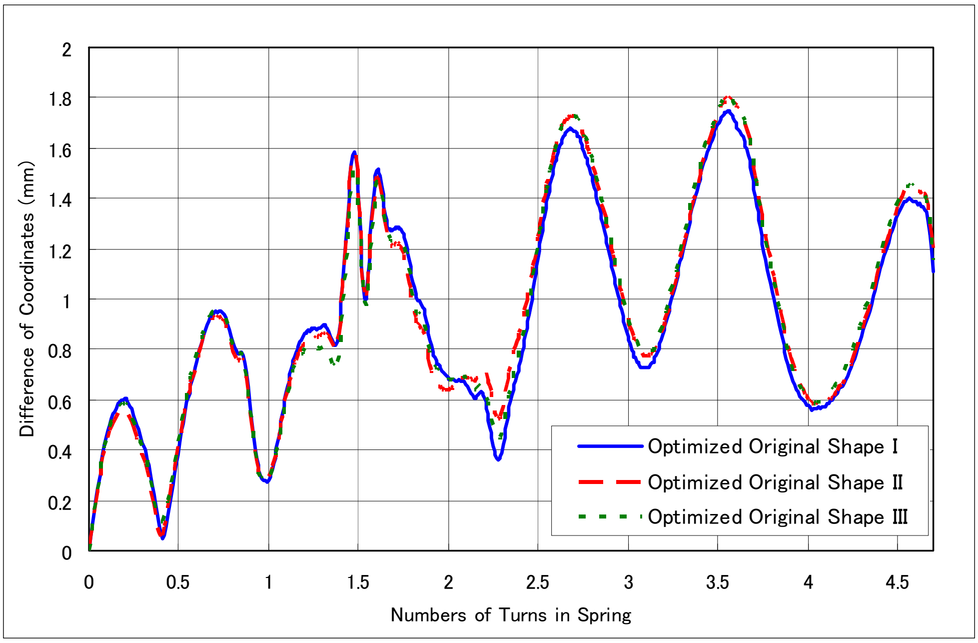


Figure 11. Comparison of Optimized Original Shape

6. Conclusion

- A precise and accurate Original Shape was determined from the Prestressed Shape by the proposed solution method for an inverse problem including significant plastic deformation by integrating Isight and Abaqus.
- Nearly identical Original Shapes were generated by the proposed solution method regardless of the Assumed Original Shape. The Assumed Original Shape had only a minor effect on convergence.
- This solution showed that Isight in tandem with Abaqus can be used to automate shape change calculations at each iteration, making the inverse solving of a shape with significant plastic deformation easy.