NANOMATERIALS
SCIENCE & ENGINEERING
Vol. 1, No. 1, pp. 50-58 (2019)

RESEARCH ARTICLE

https://proa.ua.pt/index.php/nmse/

Comparison between linear and nonlinear tolerance analysis of flexible assembly taking into account spot welding effects

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Received 16 October 2019; accepted 5 December 2019; published online 19 December 2019

ABSTRACT

The tolerance analysis for flexible parts and assemblies is the precious step in manufacturing parts in industry. In order to minimize the cost of the process, the literature has focused on reviewing tolerance analysis for flexible parts and assemblies. In this paper, are developed two major methods of tolerance analysis for flexible assemblies. Furthermore, to improve the performance of the proposed model that has been simulated to predict the deformation of flexible parts and assemblies, we have taken into account the spot-welding effects. Finally, through a comparative study, the results prove the performances of the proposed approach.

1. INTRODUCTION

The technological choices were naturally oriented towards the use of flexible parts and assemblies because of the competition between industry for Sustainable development, energy saving, carbon footprint. The latter therefore offer flexibility for some directions of solicitation, which generates defects which can be categorized as follows two principal defects position, orientation or form. They are mainly derived from manufacturing processes, and accumulate during the assembly progresses.

Liu and Hu [1, 2] proposed methods of tolerance analysis of for non-rigid sheet metal assembly, this method is based on linear elastic mechanics relation between part deviation and to analyze the effect deformation and spring-back of the assembly by the construction of a sensitivity matrix to establishes the linear relationship between the part variation and the output assembly variation. This approach called Method of Influence Coefficients (MIC). Alain Stricher, in his paper [3], proposes to perform tolerance analysis on compliant structure by limiting the shape defects and connection defects in accordance to mechanical criteria with the method (MIC). As well as in his thesis [4] the objective is to enrich the method by taking into account the deformations of the parts involved by their assembly and their geometrical defects and the development of assembly assistance software. Due to the positioning errors of the plates, the defects geometry of the assembled structure can be caused whatever the assembly method used it the idea presented by Camelio and al [5].

To optimize the tolerance of the flexible parts and assemblies, [6, 7] introduce in the first step the factors influence the final quality of the assemblies. The first paper has for objective to study the model of simulation of the variation of flexible mechanisms, using the Influence Coefficient Method taking into account the effects of contact between the surfaces and including welding distortion. In the second paper, we propose a new approach which takes into account shape defects based on the Influence Coefficient Method. Two models have been proposed to express tolerances and conduct tolerance analysis that gives more precise results; these methods are qualified as local and global methods [8]. The local method is based on the iterative calculation of mesh regularization. The global method is based on finite element analysis, with manufacturing deviations added to the nominal model by the penalty function approach. For the same aim of tolerance optimizing, the previous paper presents a new model to consider the form defects in an assembly simulation. A Metric Modal Decomposition (MMD) method is henceforth, developed to model the form defects of various parts in a mechanism. To achieve the automatic assembly of large-scale thin-walled structures, in [9] we propose to calculate the sizing force of the structures with deviations, and to study its assembling ability before assembly process, to establish a precise model to describe the deviations of structures and to study the variation propagation during assembly process. In the work [10], the objective was to present the influence of form deviations on the tolerance analysis of an assembly. For this they study initially the tolerance analysis using the deviations and clearances domains method, and in second time they integrate the influence of form tolerances on the allowable deviation domain.

2. THE NONLINEAR ANALYSIS METHOD OF FLEXIBLE ASSEMBLIES

To simulation sheet metal assemblies process it is very common, in various articles, to use Direct Monte Carlo Simulation with the introduction of the concept: cycle "CPRF" (Square Clamp Fasten and Release). The target is to predict the assembly variation based on parts variation. The snag is how much the variation of the assembly will be influenced by the parts variations (Figure1).

The behaviour of a part is expressed when the parts are loaded onto the work holding fixture. At that time the parts variations are recorded in vector $\{V_u\}$. Then the parts are forced to reach them nominal position, the first implementation of Finite element Method (FEM) is to calculate the forces applied to make the parts in them nominal position $\{F_u\}$ using the equation (1).
$[K_u]$ is the stiffness matrix of the structures.

$$\{F_u\} = [K_u]\{V_u\} \tag{1}$$

After that the parts are joined. The stiffness matrix raise from the matrix of the parts $[\mathrm{K_u}]$ to the matrix of the assembly $[\mathrm{K_w}]$. After we release of the assembled structure, the assembly will undergo spring-back from its nominal position.

$$\begin{cases} [K_w]\{U_w\} = \{F_w\} \\ \{U_w\} = [K_w]^{-1}\{F_w\} \end{cases} \tag{2}$$

Where $\{U_w\}$ is the spring-back of the assembly structures and $\{F_w\}$ is the force vector.
$\{\mathrm{F_w}\} = \{\mathrm{F_u}\}$ which connected between the spring-back $\{U_w\}$ of the assembled structure and the part deviations $\{V_u\}$ of the unassembled structure.

Figure 1. Nonlinear analysis method of flexible assemblies.

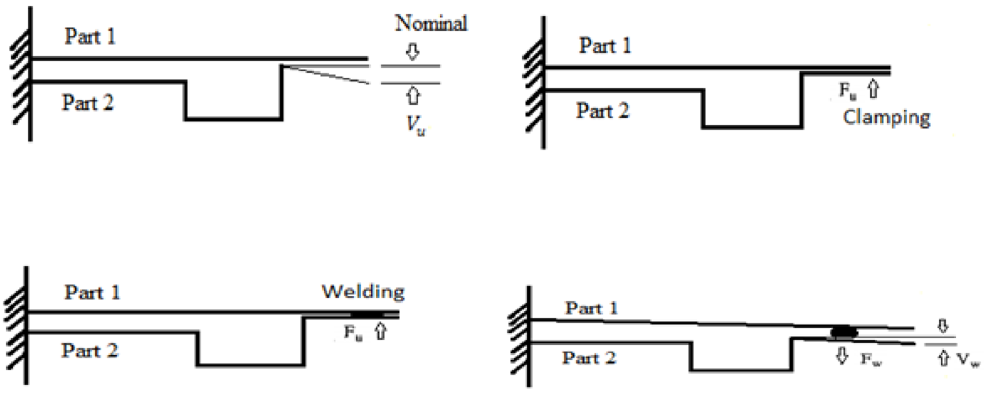

Figure 2. Cycle "CPRF" (Square Clamp Fasten and Release).

3. THE LINEAR ANALYSIS METHOD OF FLEXIBLE ASSEMBLIES

The principle of the Influence Coefficient Method is to establish a linear model between part deviations and assembly springback deviations, and that's why it is a way of performing the simulation faster than direct Monte Carlo. This method consists of three steps:

1. Force response on the displacements:

A unit force is applied to the j-th source of variation (j=1 to N) on the part. The source of variation could be any type of variation that the part will be subjected to. The response under that unit force the deformation of the part is calculated by Finite Element Analysis (FEA), and the displacements (i =1 to M) of the parts are recorded into a column vector Cj. We consider that the system is applied by an arbitrary combination of N forces (Fj, j=1 to N). [C] Is the matrix of Influence Coefficients and the vector {V} represents the deviations at the sources of variation.

$$\{\mathrm{V}\} = [\mathrm{C}]\{\mathrm{F}\} \tag{3}$$

2. Force response on the fixture points:

In step one, when a unit force is applied to the j-th source of variation, the reaction forces of the fixture points are recorded into a column vector Dj. The reaction forces R are the forces released during the springback process and [f] is the applied forces.

$$\{R\} = [D]\{f\} \tag{4}$$

3. Springback calculation of the assembly:

The springback displacements for the assembly are calculated with FEA similarly to step 1. The displacements of the points of interest are recorded into a column vector ***Sj*** for the assembly or the join parts. Here, the forces F are applied only to the

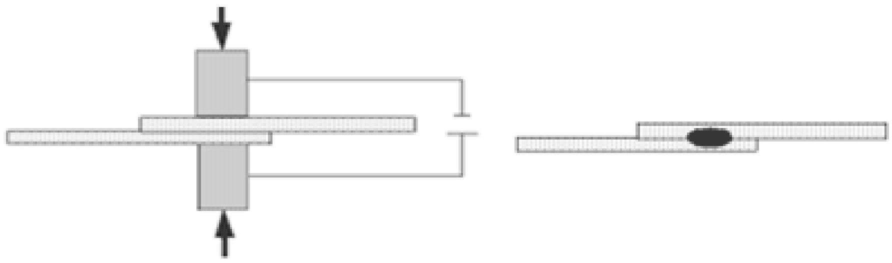

Figure 3. Two parts before and after they are joined together

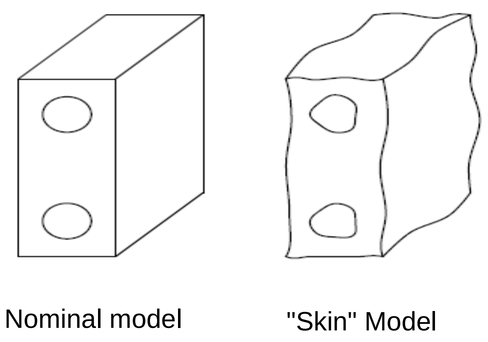

Figure 4. Skin-model concept.

fixture points or clamps that are released when the joining is done. Linear models between the applied forces F on the released fixture points and the springback displacements on final assembly could be derived by combining all the vectors ***Sj*** into a matrix:

$$\{U\} = [S]\{V\} \quad (5)$$

4. SPOT WELDING

A spot welding is modeled by a connection that passes through a point and connects two surfaces. Welds connect two or more thin overlapping metal sheets at small areas without using any filling material. Practical considerations set the limit on the total thickness of the joined sheets. The sheets are joined by applying local pressure and heat using shaped copper alloy electrodes. The electrodes apply adequate energy to cause the materials of the sheets to melt and mix together. After removing the electrodes, the melted material solidifies forming a nugget as shown in the Figure 3.

5. SKIN-MODEL CONCEPT

The "skin" model (Figure 4) that represents the interface of the part with its environment, with its defects. It differs from the nominal model that considers the parts with a perfect geometry.

6. PROPOSED METHODS

It is well known that there are many even contacts during the assembly process, such as contact between sample surfaces, contact between surfaces with fastening constraints, and the effect of tools (such as pistols welding). These paired contacts form the contact that propagate afterwards, and that caused the accumulating and stack dimensional variations. For the assembly of non-rigid parts, the deformation of the assembly makes the dimensional modeling more complex because of the propagation of variation of the parts, variations of the tool, and the deformation of contact after assembly.

In this part, the joining surfaces are supposed to be welded. Based on the flexible two-piece modeling assembly process, a new method for analyzing nonlinear contact modeling variation is proposed. Components are loaded and placed on fixed devices subsequently welded and release in the last phase according to the cycle "CPRF".

The procedure for performing a FEA, contact analysis is described by the steps shown in the following figure. As a result of the changes made for the improvement of the step method to create, the initial deformation the contact pattern is to identify where the contact could occur. For non-rigid assembly, the joint areas must be in contact. However, it is necessary to check if other areas are contacted during the assembly process. The targeted contact surfaces are defined for each pair of contacts are generated.

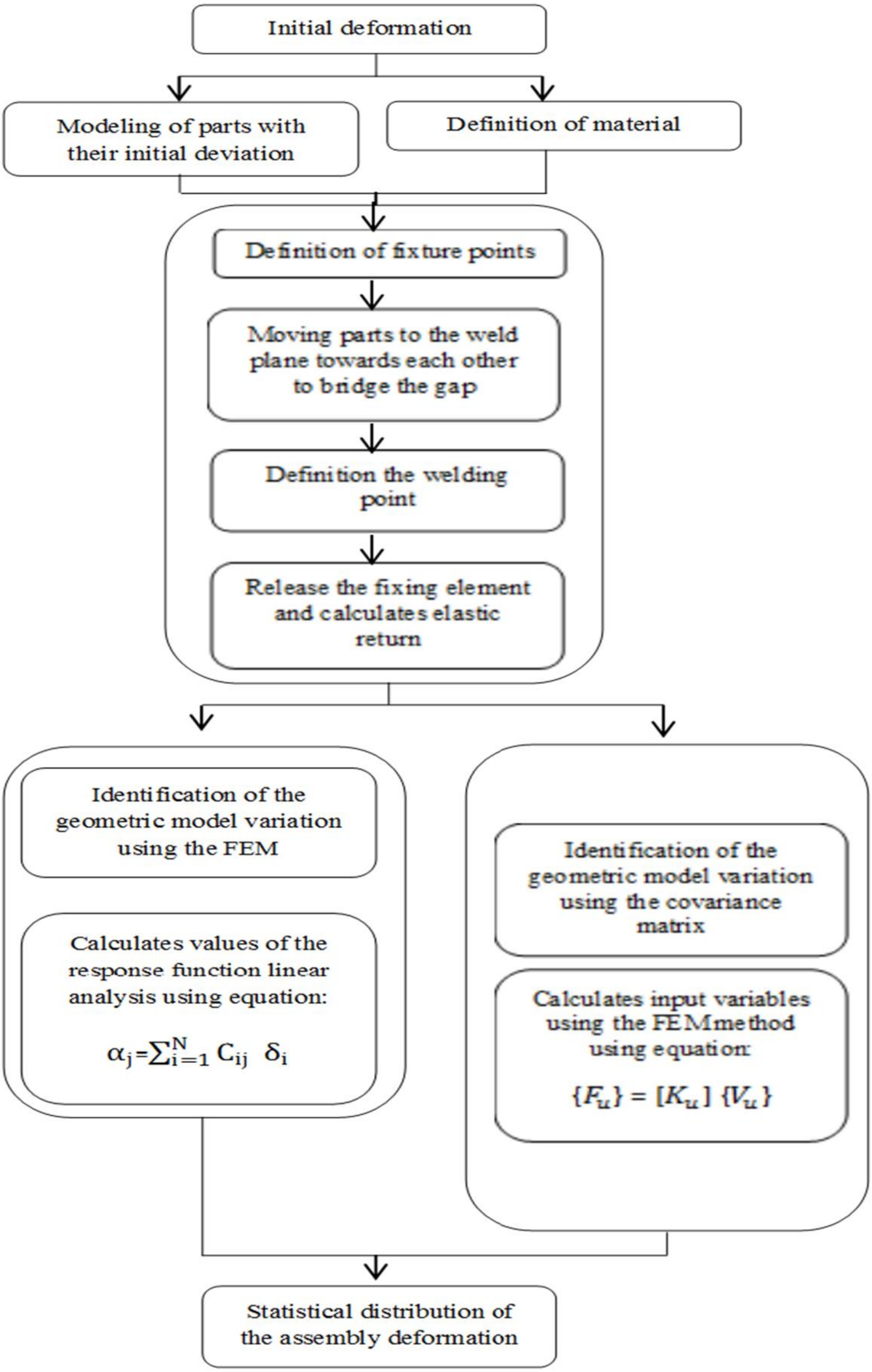

Figure 5. Finite element modeling non-linear analysis and Influence Coefficient Method linear analysis of the flexible assembly process.

The first one is the Influence Coefficient Method for tolerancing of flexible parts and assemblies corresponds to a method of disturbance where the quantities of interest that will be noted αj as the sum of the products of each contributor, denoted δi and of coefficients of influence cij determined by assembly simulations of these parts. The equation shows this approximation in index and matrix notation.

$$\alpha_j = \sum_{i=1}^{N} C_{ij}\ \delta_i \tag{6}$$

The Influence Coefficient Method supposed linear C_{ij} characterize the influence that the contributor numbered i on the quantity of interest numbered j. The matrix [S] is the "sensitivity matrix"; it contains all the influence coefficients of the contributor on the quantity of interest.

The second one is the nonlinear method based also on the FEM. The proposal method is shown in the Figure 5.

7. ANALYSIS MODEL AND LOADING CONDITIONS

Figures 6,7 show the analysis model which consists of two parts of sheet metal with 0,5 mm thick for both of them. The two parts are superposed, and two copper alloy electrodes are simultaneously used to clamp the sheets together. The surfaces are only mechanically contacted.

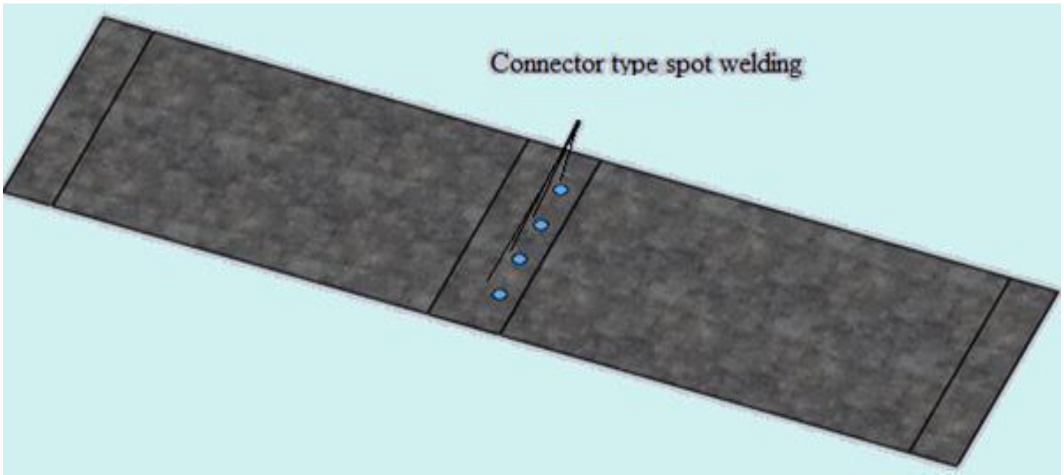

Figure 6. Geometrical model of the plate assembly.

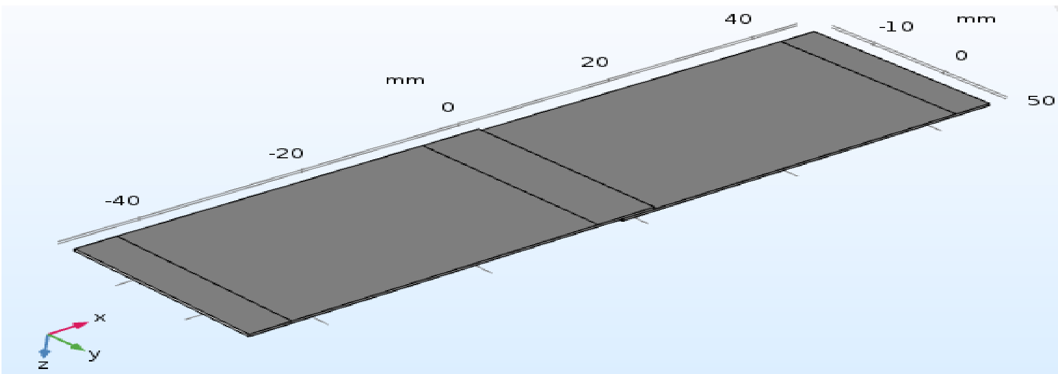

Figure 7. Plate geometry.

7.1 Object of the study

The aim of this study is to analyze the influence of these deviations on final product; one solution is to generate the Skin Model Shape based on a linear to simulate assembly with the consideration of spot-welding effects, the second one is to generate the Skin Model Shape this time based on a nonlinear to simulate assembly with the consideration of spot-welding effects. The global principle of both of the methods is based on finite element analysis. The first one is nonlinear finite element analysis but then we use a linear method Influence Coefficient (MIC) with the linearization of the deviations by the spot-welding function approach. In order to check the geometrical conformity of the both simulation of the assemblies knowing that the connection is a spot welding. We will model faults of 2000 assembly; the contributors have a normal distribution with a mean $\mu = 0$ and a standard deviation $\sigma = 1$.

7. 2. Results

An assembly of two identical flat sheet metal components by spot welding shown in the previous figure is employed to illustrate the proposed method. The parts are modeled and meshed with linear and nonlinear elements using the ABAQUS software. The set consists of 4400 elements. The sources of variation of the piece are considerate and declared with the same software. The discretization of the problem is presented in Figure 8.

In order to verify and test the implemented spot-welding effects algorithm in MIC and FEA, two different simulations for the same geometry and variation are performed:

- Influence Coefficient Method with the consideration of spot-welding effects (linear)
- Finite element analysis with the consideration of spot-welding effects (nonlinear).

The final displacement for all nodes after the springback deflection is recorded and presented for all iteration in Figure 9 and 10. The same set of variables has been used in all simulations.

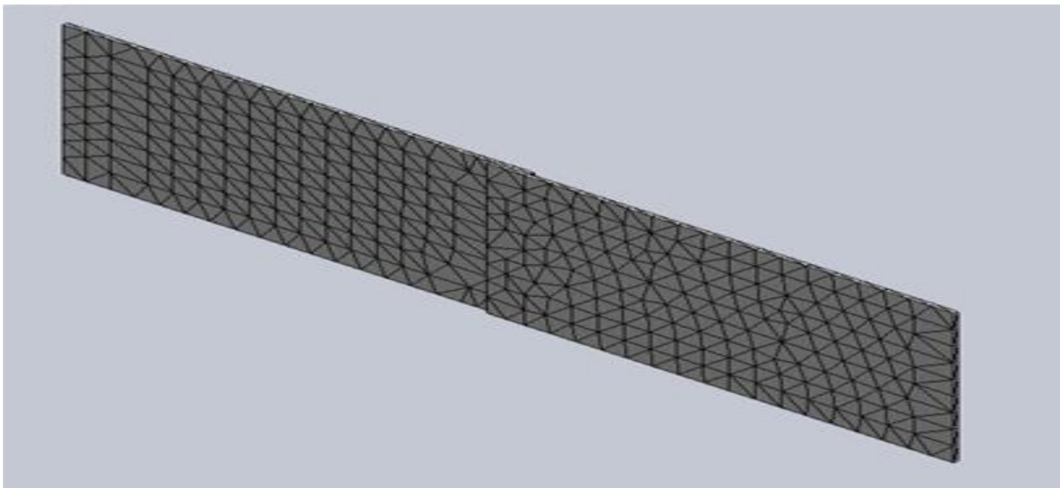

Figure 8. The finite element computation model of two sheet metal parts assembly.

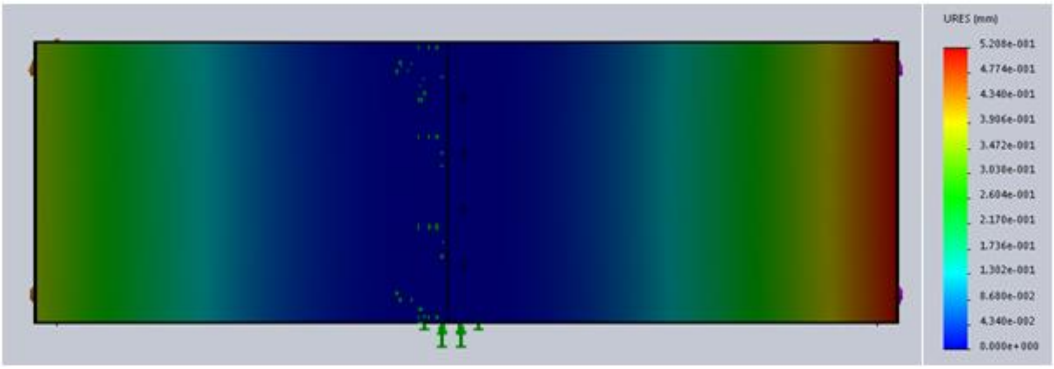

Figure 9. Results of the distribution of the dimensional variations of the assembly by the modelization with spot welding by MIC.

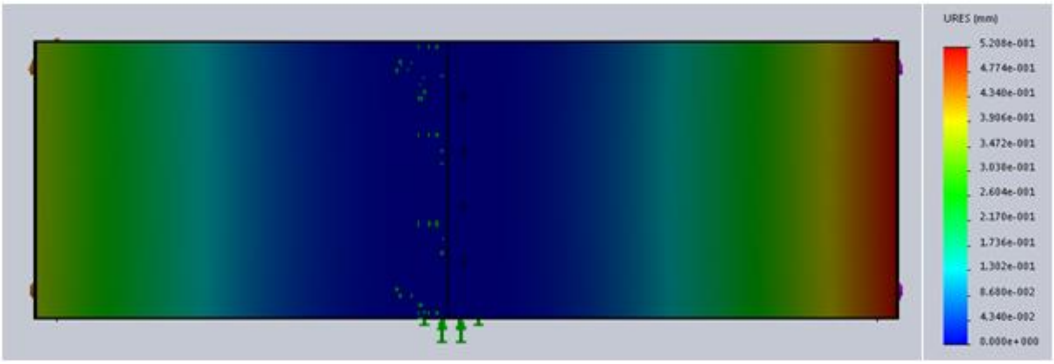

Figure 10. Results of the distribution of the dimensional variations of the assembly by the modelization with spot welding by non-linear method.

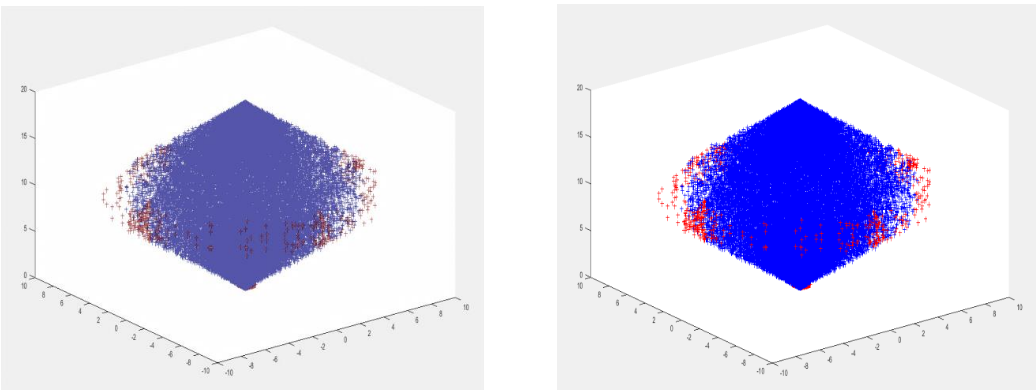

Figure 11. Geometrical conformity of the assemblies with nonlinear analysis with spot welding and, linear analysis with spot welding.

To verify the geometrical conformity of the assemblies knowing that the connection is complete, we will model the defects of 2000 assemblies. The contributors have a normal distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$. The results of the simulation are shown in Figure 11. The observed non-compliance rate is 4.05% for nonlinear analysis with spot welding and 4.042 for linear analysis with spot welding.

The comparison shows that the result of the Influence Coefficient Method (MIC) with the consideration of spot-welding effects (linear) is almost identical to the result of the Finite element analysis with the consideration of spot-welding effects (nonlinear). This means that the MIC method with linear variation can be used for the simulation and analysis of deformable assemblies.

CONCLUSION

We compare two results obtained from the simulations of the parts with two solutions. The first solution is to generate the Skin Model Shape based on a linear to simulate assembly with the consideration of spot-welding effects, the second one is to generate the Skin Model Shape this time based on a nonlinear to simulate assembly with the consideration of spot-welding effects; in order to check the geometrical conformity of the both simulation of the assemblies. According to the last simulations the comparison shows that the result of the linear simulate assembly is almost identical to the result of a nonlinear simulate assembly. This means that the linear simulation of the flexible assembly with the consideration of spot-welding effects can be used for simulation and analysis of flexible assemblies with a high precision and in a very short time with 7 second by contributing to 1236 second for the nonlinear simulation the assembly with the consideration of spot-welding effects.

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