Variation analysis of compliant assemblies: A comparative study of a single-station assembly

FRANCIOSA, Pasquale
GERBINO, Salvatore
PATALANO, Stanislao

University of Molise
University of Naples Federico II

ABSTRACT

Predicting the final shape variation of single and multi-station assemblies of compliant parts is a strategic topic especially in automotive and aeronautic industries for the wide-spread presence of sheet-metal assembly processes. The high flexibility of compliant parts causes wide final shape variations during the assembly process. Therefore, it is strategic to analyze different assembly configurations at the beginning of the design phase. Starting from the recent methodology proposed by the same authors in a previous paper to do tolerance/variation analysis of compliant assemblies in single- and multi-station configurations, the developed MATLAB-based tool, called SVA-FEA (Statistical Variation Analysis & Finite Element Analysis), is here briefly illustrated. SVA-FEA allows to pre-process FE models, imported from MSC.Patran® or HyperMesh®, defining input deviations and output variables, and including contacts between parts. Then, the results obtained with a linearization process by the MSC.Nastran® solver can be post-processed to evaluate the statistical variations - in term of mean and standard deviations - of all the points of interest. The paper presents the comparative study of tolerance/variation analysis, performed on an single-station assembly of two sheet-metal parts, between SVA-FEA and a commercial CAT system (TAA® module of CATIA® CAD system). The main differences between the two analysis tools are finally outlined.

Keywords: Tolerance Analysis, Compliant Assembly, Comparative Study, Finite Element Analysis.

1. Introduction

The assembly process may be strongly affected by part variations (limited by manufacturing tolerances) and assembly sequence. But the assembly phase itself may influence the final shape of the released assembly. This is true especially for compliant assembly, such as those involving sheet-metal parts. In these cases, dimensional and geometrical tolerances alone cannot predict the real shape of the released assembly, because the elastic behaviour of the flexible parts may influence strongly how parts and (sub-) assemblies deform. In the last decade the interest for the variation analysis of compliant assembly is growth and many researchers have addressed their attention to modelling how to predict the variation at assembly level when the variation at part level for compliant parts is known. The proposed methods may be distinguished in variation analysis of single-station assembly and multi-station assembly. The latter considers also the accumulation effect when sub-assemblies are moved and repositioned station to station during the assembly process. Among the single-station assembly methods we may mention [2] in which a contact chain graph to analyze how errors accumulate in assembling non-rigid parts following the PCFR (Place, Clamp, Fasten, Release) cycle is proposed. A milestone in the present topic has been proposed by Liu and Hu [7] for single-station compliant assemblies by using the method of influence coefficient, MIC. That work then has been extended to multi-station assemblies by Camelio et al. [1] using a different approach based on the 'Stream-of-Variation' by Hu [6]. In [9] a robustness approach is used to evaluate the geometric sensitivity of a part or assembly to part variations. In [8] the unit displacement method is introduced, similar to MIC, taking into account three kinds of variations: positioning, shape and conformity variability. This methodology has been later implemented and extended in the TAA® module (Tolerance Analysis of deformable Assembly), available in CATIA® CAD system by Dassault Systèmes. In the original MIC, parts are allowed to penetrate each other. To avoid this, in [3] a new model with contacts has been introduced. Recently, starting from MIC, a new methodology has been proposed which allows to analyse assembly both in single- and in multi-station configurations with contact elements [5]. In the next section this methodology is summarised. The derived so-called SVA-FEA (Statistical Variation Analysis & Finite Element Analysis) environment is here tested on a single-station assembly of two sheet-metal parts. A comparative study of variation analysis between SVA-FEA and a commercial CAT system (TAA® module of CATIA® CAD system) is then shown. The main differences between the two analysis tools are finally outlined.

2. SVA-FEA methodology overview

In the following, the main features of the SVA-FEA methodology are summarised. Further details are in [5]. The SVA-FEA methodology allows to simulate the variability accumulation in multi-station assembly processes. The linear relationship between variations, at part level, and deviations, at assembly level, can be written as:

$$\{V_A\} = \{S\} \cdot \{V_{VAR}\} \qquad (1)$$

where $\{V_A\}$ is the deviation vector at assembly level, $\{V_{VAR}\}$ is the variation vector at part level, and [S] is the global sensitivity matrix. So the equation (1) describes how sensitive is the assembly to variations at part level. The matrix [S] can be decomposed into N sub-matrices, related to each assembly station, as in equation (2),

$$[S] = [S_1, S_2 .., S_i, .., S_N] \qquad (2)$$

where N is the number of assembly sub-stations. The methodology proposed in Gerbino et al. [5] to evaluate the local sensitivity matrix [Si] is based on two consecutive FEA runs. In the first one, the influence coefficients method is used to calculate fastening and fixturing forces in all points of interest. Opposite forces are applied in the second FEA run to simulate the elastic spring-back effect occurring during the releasing phase of fastening and fixturing tools. Then, the local sensitivity matrix is calculated. The generic element Sij measures the sensitivity (in terms of displacements) of assembly at the i-th node due to the incoming part deviation at the j-th node. The proposed linear model is acceptable if elastic behaviour of each part and small displacements are assumed. Statistical distributions of deviations at assembly level can be carried out using the relationship (1). Applying the expected value operator, equation (1) becomes:

$$\{\mu_A\} = [S]_\mu \cdot |\{\mu_{VAR}\}| \qquad (3)$$

where $[S]_\mu$ is the mean reduced sensitivity matrix [5], while $\{\mu_{VAR}\}$ and $\{\mu_A\}$ are the mean input deviation vector at part level, and the mean output vector at assembly level, respectively. In addition, the assembly standard deviation vector can be calculated by equation (4):

$$\{\sigma_A\} = \sqrt{[S]^2_\sigma \cdot \{\sigma_{VAR}\}^2} \quad (4)$$

where $[S]_\sigma$ is the standard deviation reduced matrix [5], whereas $\{\sigma_{VAR}\}$ and $\{\sigma_A\}$ are the input standard deviation vector at part level and the output standard deviation vector at assembly level, respectively. No geometric covariance is taken into account: all input variability is assumed to be a statistical set of independent variables. In order to avoid part to part penetration during spring-back phase, 'linear contact' elements are considered. By using the tools available in MSC.Nastran® [11] it is possible to implement linear contacts through MPC (Multi-Point Constraint) elements.

3. SVA-FEA interface

The SVA-FEA methodology summarised in section 2 was implemented in a Graphic User Interface (GUI) fully developed in MATLAB [10] environment. Figure 1 shows the SVA-FEA user interface. The FEM model can be imported from any pre-processor tool in the MSC.Nastran® format (*Bulk Data format*). The MATLAB's GUI drives the user to define fixturing, fastening and contact points with their variability. Fixturing points can be set in the *CONSTRAINT* menu. Each fixturing point is modelled as a kinematic joint, assigning the related degrees of freedom. The *FASTEN* menu allows to create, edit or delete fastening set points. Deterministic thermal load can be also applied. In order to take into account the gravity effect on the final assembly shape, fastening masses can be added.

The CONTACT menu allows to assign contact set points, wherever necessary. Each contact pair is introduced by defining a master part and a slave part. FE analysis is run in background mode. The output variables are the statistical variations at the nodes of interest, calculated through equations (3) and (4). Final assembly shape is shown in terms of mean values (mean deformation plot), and contour plots can be displayed for mean and for mean ±3σ, along each global axis.

4. Case study: Comparative analysis

The SVA-FEA variation assembly methodology was tested on an assembly of two aluminum sheet-metal parts (Young's Modulus E=70.000 N/mm^2; Poisson's ratio Ó=0.346; uniform thickness T=2 mm), shown in figure 2.

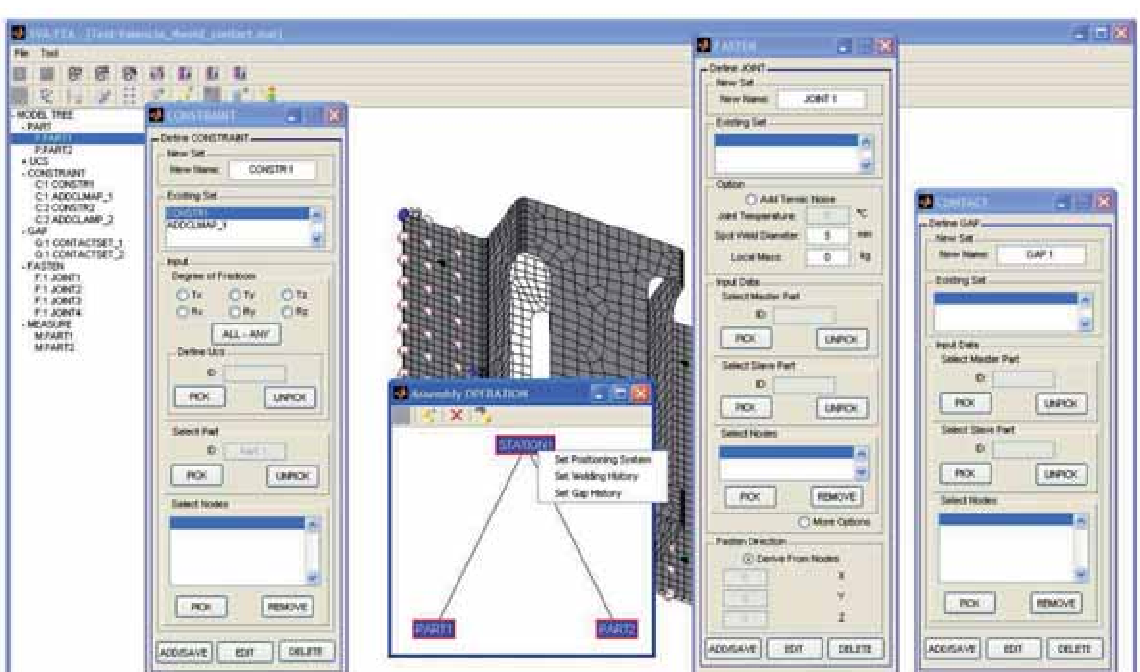

Figure 1. SVA-FEA user interface

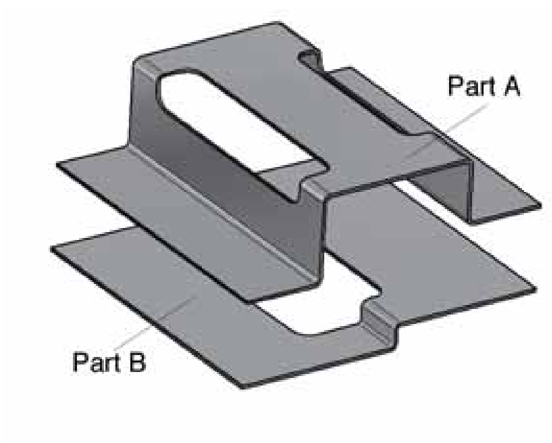

Figure 2. Assembly geometry

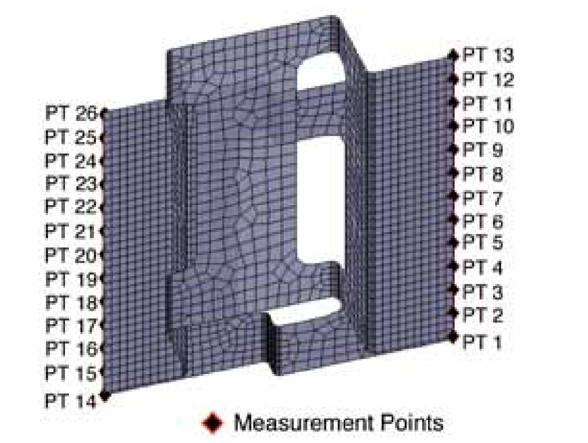

Figure 3. Assembly measurement points

The overall dimensions of the assembly are 200x200x60 mm. The TAA® module of CATIA® [12] was also tested, and both results were then compared. Simulation results were performed on the measurement points shown in figure 3: points 1 to 13 are related to part A, 14 to 26 to part B. Mid-surfaces were extracted from the CAD models and then meshed with shell elements.

Global mesh element size was equal to 5mm. Figure 4 shows the final model within SVA-FEA environment. Each fixturing point was modelled as a spherical joint: only translations are constrained. Fastening points were modelled as CWELD elastic connector elements, available in MSC.Nastran®. Local input variability was applied at fastening points in the global X axis. Table 1 shows the adopted statistical values. Part A was assumed with an initial zero variation. The TAA® model (figure 5), related to the present case study, was based on the following features: mesh elements were imported from SVA-FEA model; fastening joints were modelled as weld spots; local input deviations were applied at fastening points; and, additional clamps were added to fastening points in the positioning phase. In this way, during the positioning phase, fastening and fixturing tools were closed to their nominal position.

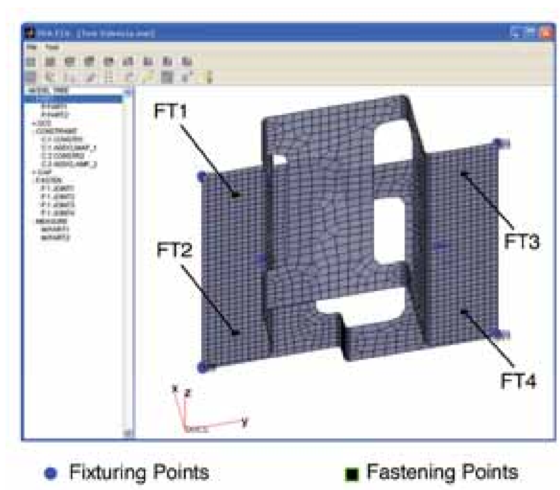

Figure 4. SVA-FEA model

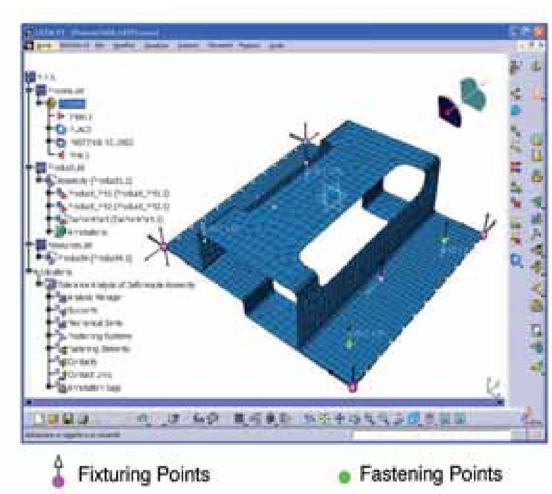

Figure 5. TAA model

5. Results and discussion

Figures 6 and 7 show the assembly mean deformation evaluated in SVA-FEA and TAA® environments, respectively. The assembly configuration is related to the releasing phase of fastening guns. The influence of the number of fastening points is of interest. Therefore, four

	Weld points	Mean X (mm)	Std Dev X (mm)
Part A	FT1	0.0	0.0
	FT2	0.0	0.0
	FT3	0.0	0.0
	FT4	0.0	0.0
Part B	FT1	-0.3	1.0
	FT2	1.0	1.5
	FT3	-0.6	1.0
	FT4	1.0	1.0

Table 1. Statistical input variability

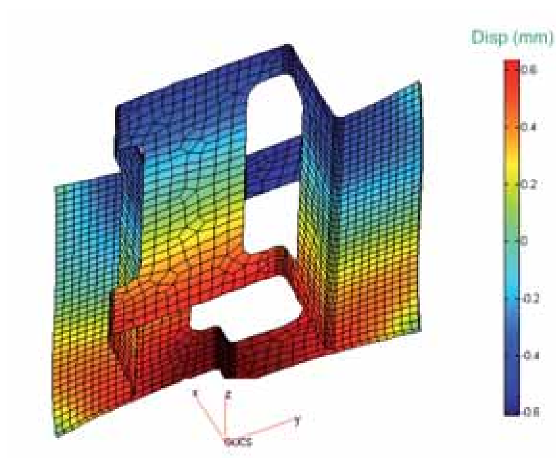

Figure 6. SVA-FEA results. Contourplot shows mean displacements along global X axis

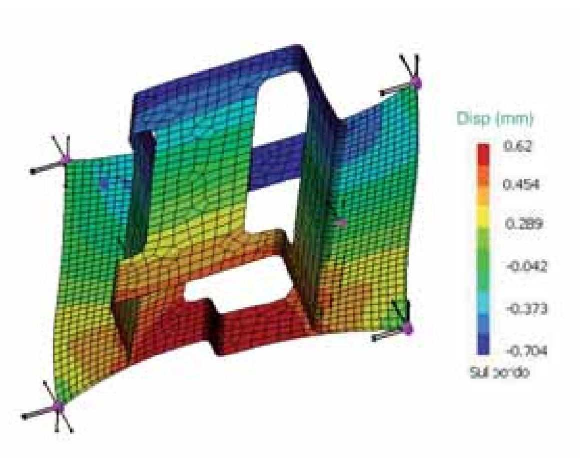

Figure 7. TAA results. Contour plot shows mean displacements along global X axis

kinds of configurations were analysed: fastening point FT1, fastening points FT1+FT2, fastening points FT1+FT2+FT3, and fastening points FT1+FT2+FT3+FT4 (see figure 4). Figures 8 and 9 show the output deviations, related to measurement points (figure 3), in terms of mean and standard deviation, respectively.

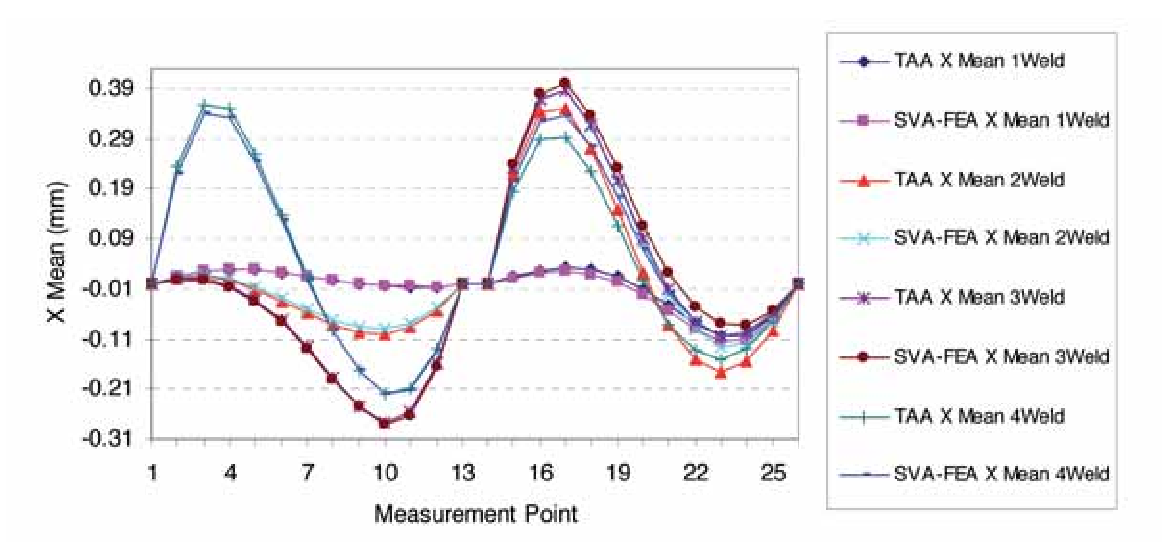

Figure 8. Mean deviations at measerument points along global X axis

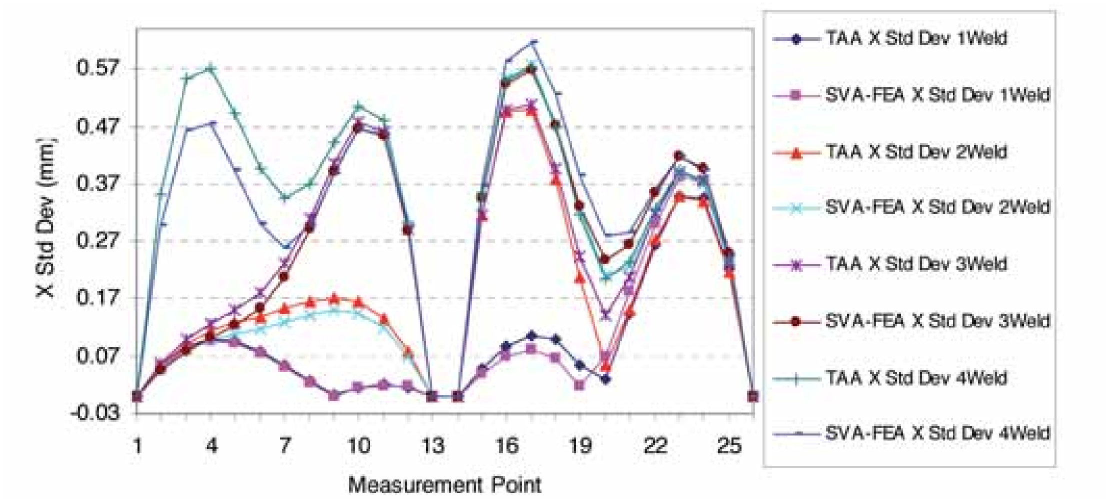

Figure 9. Standard deviations at measurement points along global X axis

The results show that final assembly deviations are highly influenced by the number of fastening points. Moreover, SVA-FEA and TAA® results are highly correlated, as shown in table 2. The following correlation index was used:

$$\rho(x,y) = \frac{cov(x,y)}{\sqrt{\sigma_x^2 \cdot \sigma_y^2}} \quad (6)$$

where x and y are the data sets, Ûx and Ûy are the related standard deviations, and cov(x,y) is the statistical covariance of data sets [4]. In order to estimate the numerical error between SVA-FEA and TAA® results, an RSS (Root Sum Square) index error was adopted. Table 3 shows the RSS index both for mean deviation and standard deviation values. In the configuration "FT1+FT2+FT3+FT4" numerical error, related to standard deviations, is about 5.5%.

This is mainly due to the different way to model fastening points in SVA-FEA and TAA. In TAA® they are assumed as kinematic joints (spherical or revolute joints [12]). Instead, in SVA-FEA they are assumed as elastic beams linking the mating parts. These assumptions influence final assembly deviations.

Configuration	Correlation (Mean)	Correlation (Std Dev)
FT1	0.995	0.988
FT1+FT2	0.989	0.965
FT1+FT2+FT3	0.998	0.979
FT1+FT2+FT3+FT4	0.988	0.952

Table 2. Correlation indexes

Configuration	RSS% (Mean)	RSS% (Std Dev)
FT1	0.464	2.021
FT1+FT2	2.188	4.877
FT1+FT2+FT3	1.221	3.713
FT1+FT2+FT3+FT4	2.826	5.486

Table 3. Percentage RSS errors

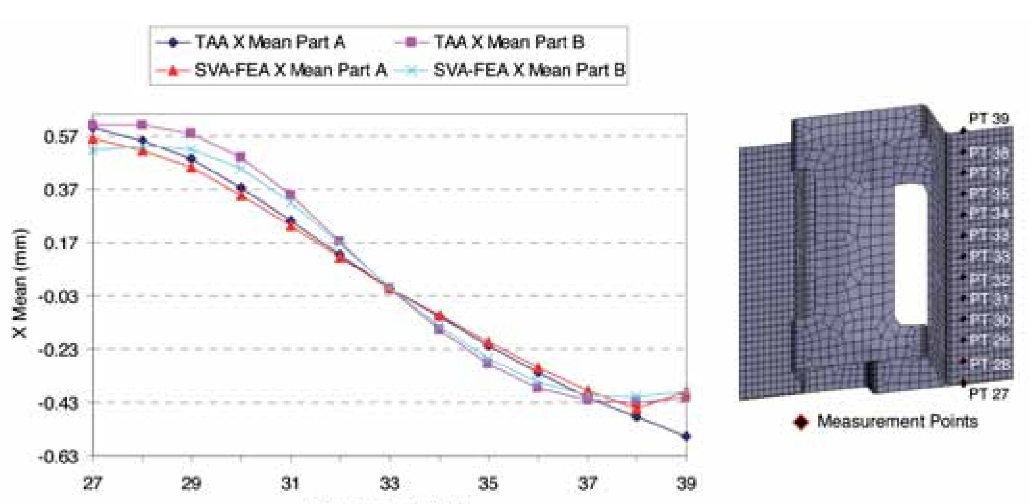

Figure 10. Mean deviations at measurement points on parts A and B

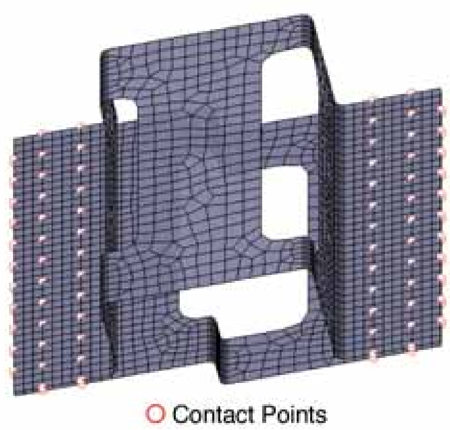

Figure 11. SVA-FEA contact points

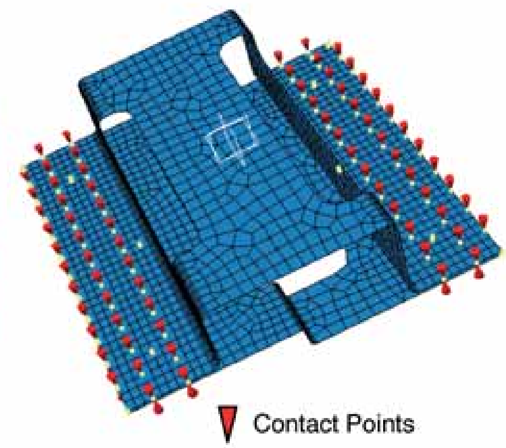

Figure 12. TAA contact points

In the simulations performed on the assembly parts intersect each other along mating surfaces. Figure 10, in fact, shows that mean deviations of measurement points on part B are greater than ones on part A, both for SVA-FEA and TAA® results.

Generally speaking, contact elements may strongly influence final deviations of assembly and its shape ([3], [5]). In order to prevent the penetration between parts, contact points were added in SVA-FEA and TAA® models, as shown in figures 11 and 12, respectively.

Figures 13 and 14 depict results in terms of mean and standard deviation. The analyses are related to the assembly configuration "FT1+FT2+FT3+FT4". The comparison shows there are significant differences between the simulation with and without contacts in terms of mean and standard deviations. Moreover, the numerical error between SVA-FEA and TAA® results decreases when contacts are introduced. The RSS error, shown in Table 4, is less than 3% when the simulations were performed using contacts.

6. Conclusions

In this paper an in-house MATLAB-based tool, called SVA-FEA (Statistical Variation Analysis & Finite Element Analysis), has been illustrated. The tool is based on a recent new methodology proposed by the same authors. Through the MATLAB's GUI the user is driven to define contacts, fixturing and fastening points, with variability, and the assembly tree. The environment allows also to post-process and display statistical deviations at assembly level. A single-station assembly has been analyzed both in SVA-FEA and in the TAA® module of CATIA®. The numerical comparison has shown a highly correlation both for mean and standard deviations. Closer results are reached when contacts are included in the analysis.

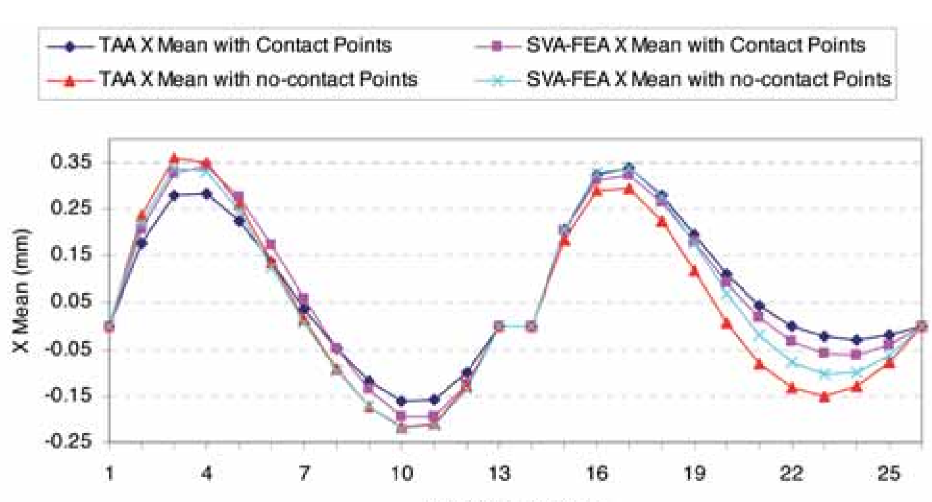

Figure 13. Mean deviations at measurement points. Contact vs no-contact analysis

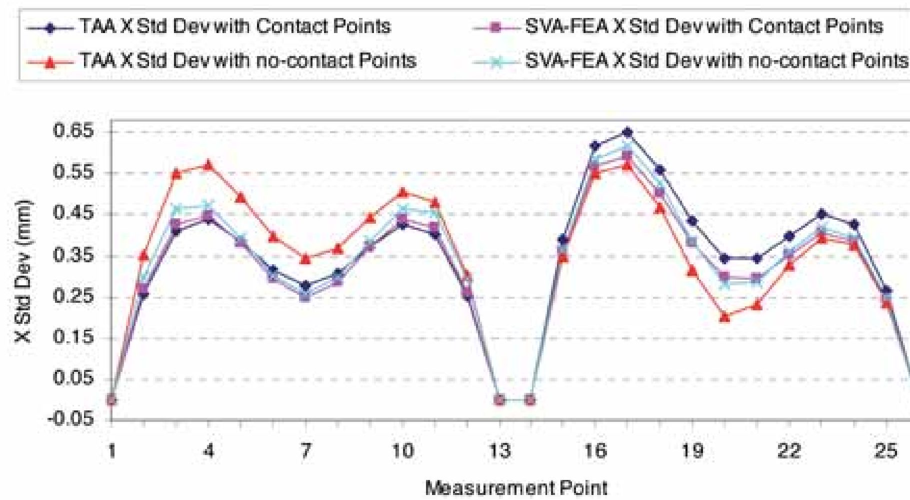

Figure 14. Standard deviations at measurement points. Contact vs no-contact analysis

	Mean Deviations		Std Dev Values	
Configuration	No-contact	Contact	No-contact	Contact
RSS error %	2.826	2.863	5.486	2.590

Table 4. Percentage RSS error. Contact vs no-contact analysis

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