Flexible Beam-Based Modeling of Sheet Metal Assembly for Dimensional Control

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ABSTRACT

In this paper, a flexible beam-based modeling method is proposed for dimensional control of the sheet metal assembly process. This method uses developed decomposition principles of key design and manufacturing characteristics for integration of assembly process and product design. It allows for modeling of assembly processes and product in the early design stage of process and product design. The method includes principles of decoupling automotive parts into beam members, beam connectivity selection, beam-to-beam joint geometry modeling, and process locating points identification. The procedure of incorporating these principles into modeling methodology for a dimensional control approach is presented. The presented modeling method was implemented to diagnose multiple dimensional faults of flexible sheet metal assembly.

INTRODUCTION

Increasing quality and productivity are two major goals in today's automotive industry. Fixture failure and dimensional variation are major factors in decreasing productivity (e.g., corrective adjustments of closure panels such as doors, fenders, and hoods) as well as quality (water leaks, wind noise, front wheel misalignment). Currently, SPC (statistical process control) is the standard method used to control the process and maintain a high dimensional quality of the product (Faltin and Tucker, 1991). However, with the recent introduction of OCMMs (optical coordinate measurement machines) and the availability of 100% measurements, advanced quality control techniques are required to take advantage of this information (Hu and Wu, 1990; Ceglarek and Shi, 1996).

A diagnostic technique based not on heuristic information but on the first principle, a system model, is necessary for today's requirement for fast model change-over (Reiter, 1987). Currently, in the area of sheet metal assembly, a method developed to model fixture failures proves the existence of a relationship between dimensional variation described by principal component analysis (PCA) and fixture tooling faults (Ceglarek and Shi, 1996). Additional development of the fixture failure identification method, using modeling technique based on the rigid body assumption, allows diagnosis of dimensional failures of sheet metal assemblies within a single assembly station and across assembly stations (Shiu et al., 1996). However, these methods assume rigidity of all assembly parts.

In the past, Lust and Bennett (1981) used skeleton body frame structures for structural stiffness optimization during the design stage. Additionally, analytical use of beam model representations, which are similar to the skeleton structure of automotive bodies, have been reported by several researchers (Fenyes, 1981; Du and Chon, 1983). A more refined generic model of a vehicular structure has been developed using the structural frames of the automotive body by Chon et al. (1986). His skeleton model is used to optimize structure design in the early autobody structure design stage, as well as joints' loading characteristics, which improves structural stiffness on torsion and bending rigidity. However, these research papers focus on the issues of crashworthiness, dynamics, and loading performance of the vehicle. The issue of sheet metal assembly design and manufacturing integration with respect to product dimensional analysis has not been examined.

This paper focuses on the development of a flexible part assembly modeling methodology for dimensional diagnostics of the automotive body assembly process. In this paper, a multiple faults are modeled based on flexible characteristics of the sheet metal, such as the automotive parts deformation under stresses or load and the part-to-part mating interactions that describe the joining conditions. A simple diagnostic reasoning strategy is used by matching the model behavior to the real behavior of an automotive body assembly process, obtained through in-line 100% measurements.

In this paper, automotive body design and structure representation will be introduced first. A review of the structure analysis will then be provided. Modeling based on the flexible automotive body structure, structure connectivity principles, and principal locating points, as well as the weld joining interactions, will be described and followed by a summary of modeling strategy. Finally, simulation results of single and multiple faults diagnostics as well as a case study based on the real industrial data are presented.

ASSEMBLY MODELING PRINCIPLES

This section presents a flexible beam modeling method that integrates sheet metal design of the product with the assembly process. The objective is to analyze the product dimensional response under assembly process conditions. Due to the complexity of the process, product structure, and design of the mating surfaces, a certain level of simplification is necessary to perform dimensional analysis and control. It will be realized by creating a simplified (beam structure) model of the automotive body to include the critical characteristics of the assembly processes, which are: (1) fixture locating and holding layout; (2) location of welding spots; and (3) type of part-to-part joints.

Modeling of an automotive body (Figure 1a) for the purpose of dimensional variability should include the structural/dimensional response of the body to external and internal stress, caused by process dimensional discrepancies and parts deviations respectively.

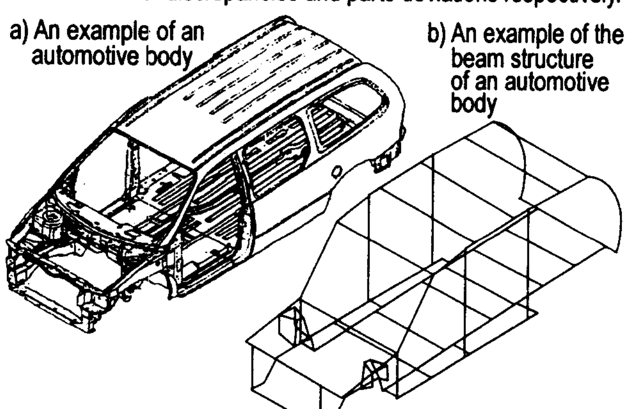


Figure 1. Automotive body and its beam structure.

In order to model the structural/dimensional response of a typical automotive body, a representative structure of the automotive part/subassembly is chosen so that its structural response to the external and internal forces and moments should be similar to the response of the actual parts and subassemblies. The modeling of the final CAD design of the automotive body is a very complicated process, due to many geometrical details that do not impact the structural/dimensional response by the assembly processes.

Currently, the most often-used structural models are based on beam structure modeling (Figure 1b). The beam-type models are based on the assumption that only the most rigid parts, such as major reinforcements, roof bows, underbody rails, and so on, will significantly contribute to the overall structural integrity of the automotive body. All these structural parts are the major load-carrying elements of the automotive body. Therefore, the representative, yet simplified, model of the automotive body has to contain all the major load-carrying elements to correctly model the dimensional/structural response of the product caused by part and process discrepancies.

The proposed modeling method uses beam elements to describe the automotive body structure. The main concept of integrating the design of the product and the manufacturing assembly process is presented in the form of four principles, which are based on the key characteristics of the automotive body structure, assembly process (welding), and types of part-to-part joints.

- The principle of decoupling the automotive body into beam elements: Defining the beam model through both the functionality and shape of the automotive parts define the definition of the beam model.
- Beam connectivity modeling principle: Identifying the connectivity among structural connecting points of the selected beam elements.
- Part locating layout principle: Identifying fixture points through the locating mechanisms which form the basic fixture points.
- The principle of beam-to-beam geometry modeling: Identifying joint geometry based on the three different basic joint types. These joint types are based on their direction of the welding forces and geometrical information.

In the following section, a review of the structure analysis will be provided. Each of the above four principles will be discussed in detail.

Review of Structure Analysis

The presented method is based on the results from structural analysis (West, 1989). The analyzed structure can be divided into nodes and beams (elements) (Figure 2).

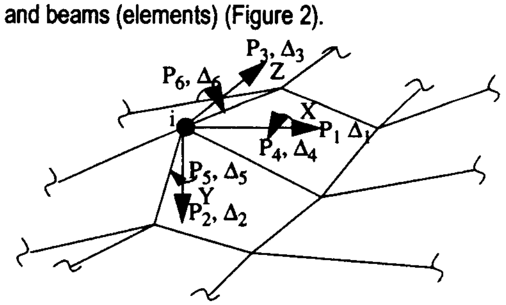


Figure 2. Structural forces and displacement.

At each node, the loading condition is specified by six generalized force components, P_1 through P_6, and the response is described by six displacement components, Δ_1 through Δ_6. These forces and displacements are shown in their positive directions at joint i. P_1, P_2, and P_3 represent the forces. P_4, P_5, and P_6 represents the moments, as shown in Equation 1. Δ_1, Δ_2, and Δ_3 represent the translational displacement components, while Δ_4, Δ_5, and Δ_6 represent the rotational displacement components, as shown in Equation 1. The right-hand rule is used to establish the positive directions between axes.

In matrix form, the forces and displacement vectors can be expressed as:

$$\{P\}_i = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 \end{bmatrix}_i^T, \{\Delta\}_i = \begin{bmatrix} \Delta_1 & \Delta_2 & \Delta_3 & \Delta_4 & \Delta_5 & \Delta_6 \end{bmatrix}_i^T \quad (1)$$

where i indicates that each element of the array is associated with joint i. The forces and displacements are applied to all nodes located on the whole structure. The forces at the nodes represent the structural loads that are directly applied to the structure, and the displacements are the responses of those applied loads. The structural forces and displacements relationship is given by

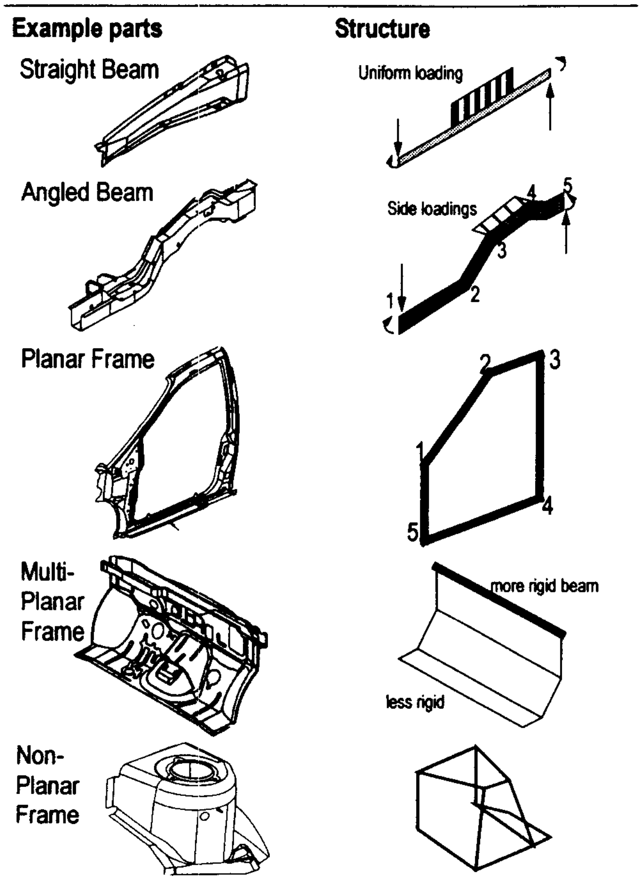
$$\{P\}_{nx1} = [K]_{nxn}\{\Delta\}_{nx1} \quad (2)$$

where [K] is defined as the total structure stiffness matrix, {P} represents the total structural forces, {Δ} describes the nodal displacements, n is the total number of nodes in the structure, $[K]_{ii}$ is the direct structure stiffness matrix, and $[K]_{ij}$ is the cross-stiffness matrix ($i=1,2,...,n; j=1,2,...,n; i \neq j$).

Principle of Decoupling Automotive Parts into Beam Elements

This section discusses the first modeling principle, decoupling the automotive body into beam elements. Table 1 shows some examples of beam members that are classified into five basic representative element types, based on the shape and functionality of the parts.

TABLE 1. Basic types of beam model structures.



(1) Straight beams are the simplest building blocks of more complicated structures. The attachment to other parts, reaction forces, and reaction moments can be considered as the loadings, end forces, and end moments. (2) Angle beams, which are modeled by multiple connected straight beams, are used when the straight beam simplification does not apply. (3) Planar frame structures can be modeled into a single plane. This structure can be identified by its flexibility and large deformable shape in one particular axis. (4) Multiple planar structures can be modeled by multiple single planes. (5) Finally, a non-planar structure can be identified as a complicated 3-D multiple-planar closed structure that cannot be simplified to a multiple planar structure.

Having defined the basic types of beam model structures, we can represent the product and its subassemblies in the following way. Figure 3 shows an example of the underbody process where the component and subassembly groups are organized in the order of assembly sequence. The underbody consists of five layers (Figure 3). Layer 1 shows the complete underbody. The complete underbody is formed by parts in Layer 2. Three major subassemblies (Layer 3) form the skeleton of the underbody, each composed of subgroups (Layer 4). Finally, each subgroup is made of stamped panels (Layer 5). Each structure shows a simplified structure in which their significant structural frames or load-carrying members are shown in Figure 2. It follows the five basic representative structure types. Each element in Figure 3 can be modeled into a simplified frame structure.

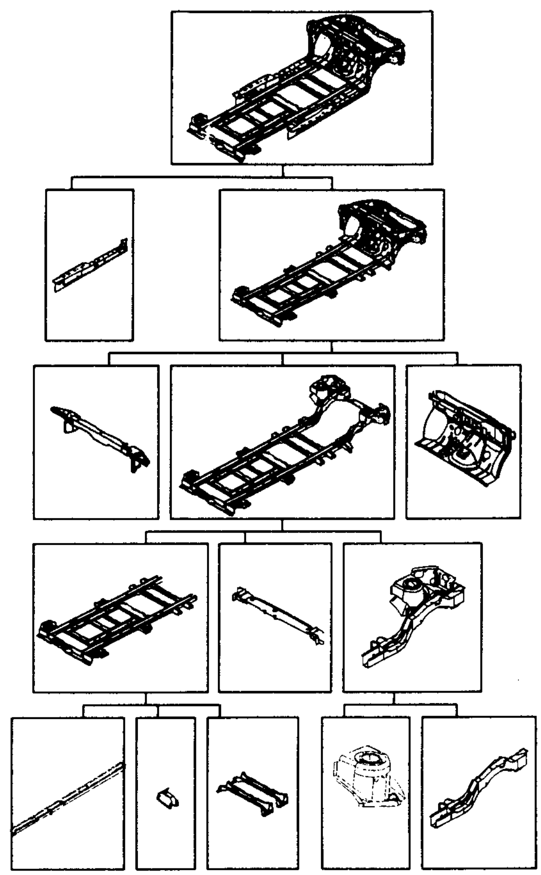


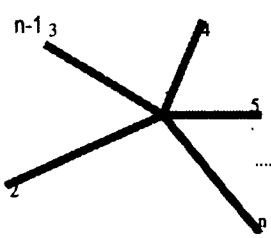
Figure 3. Underbody assembly sequence and parts

Principle of Beam Connectivity Modeling

Having defined the basic types of beam elements and their representation in the assembly process, we need to define the representation of part-to-part connectivity models or beam-to-beam connectivity. This section will discuss the structure analysis formulation of multiple beams connected to a single node. Table 2 shows the structure stiffness matrix formulation of any number of beams that are connected to a single node. Thus, any multiple connected beam at a single node can be formulated using Table 2

The structure stiffness matrix is represented for each beam-to-beam connection. The multiplicity of the nodal connection depends on the detailed design of the structure.

TABLE 2. Number of beam connected in one node

Number of Beams connected at one node	Structure stiffness matrices, [K]
One 	$\begin{bmatrix} \kappa^2_{11} & \kappa_{12} \\ \kappa_{21} & \kappa^1_{22} \end{bmatrix}$
...	...
n-1 	$\begin{bmatrix} \sum_{j=2}^{n}(\kappa^j_{11}) & \kappa_{12} & \kappa_{13} & \kappa_{14} & \dots & \kappa_{1n} \\ \kappa_{21} & \kappa^1_{22} & 0 & 0 & \dots & 0 \\ \kappa_{31} & 0 & \kappa^1_{33} & 0 & \dots & 0 \\ \kappa_{41} & 0 & 0 & \kappa^1_{44} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & 0 \\ \kappa_{n1} & 0 & 0 & 0 & 0 & \kappa^1_{nn} \end{bmatrix}$

Principle of Beam-to-Beam Joint Geometry Modeling

This section discusses the loading forces and interaction forces applied to the structure due to the assembly process and caused by welding interactions. Once parts are positioned, they are welded by the forces created by the welding process, such as heat and pressure of the weld guns.

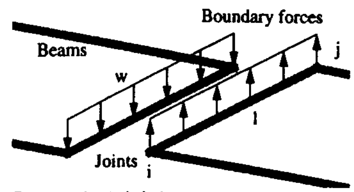
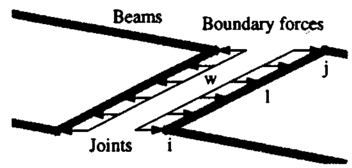
Due to the flexibility of sheet metal parts, the final parts' locations actually deviate from the original locations. The part-to-part joint interaction (assembly interactions) is important for the dimensional control. Each type of joint will undertake a different direction of interaction forces from the welding process. Currently, in the automotive body assembly process the most often-used joints can be classified into lap-to-lap, butt-to-butt, and lap-to-butt joints. Each joint represents a distinct set of interaction conditions or force loadings.

1) A lap-to-lap joint, as in Table 3, is a joint method in which two flat sheet metal pieces are joined by overlapping. A lap-to-lap joint is also called a slip plane, which provides movement in the x and y directions. The main geometrical control is in two directions, the y and x axes, because of the rigidity of the two sheet metal pieces in the x and y axes. The z direction control is more of a part-holding mechanism than a geometrical locator. The welding force on the part, as shown in Table 3, is going to be dominant in determining the location of the assembly in the z direction. Its corresponding interaction forces vector on the beam structure is shown in Table 3, where F_{ij}^{f} is the member force on the i node of member ij, and F_{ji}^{f} is that of the j node.

2) A butt-to-butt joint is two flanged sheet metal parts joined by welding the gap together. The x direction is controlled by applying clamps, which are necessary for gap closure between the two parts. The butt-to-butt joint provides a slip plane in the y and z planes. As a result, these are the only two degrees of freedom. Parts are coupled in the x direction.

3) A lap-to-butt joint interaction forces can be derived in similiar manner (Shiu, 1996).

TABLE 3. Joint-to-joint Interactions

Beam structure model	Interaction forces
Lap-to-lap joint 	$F^f_{ij} = \begin{bmatrix} 0 & 0 & \frac{wl}{2} & -\frac{wl^2}{12} & 0 & 0 \end{bmatrix}^T$ $F^f_{ji} = \begin{bmatrix} 0 & 0 & -\frac{wl}{2} & \frac{wl^2}{12} & 0 & 0 \end{bmatrix}^T$
Butt-to-butt joint 	$F^f_{ij} = \begin{bmatrix} \frac{wl}{2} & 0 & 0 & 0 & 0 & -\frac{wl^2}{12} \end{bmatrix}^T$ $F^f_{ji} = \begin{bmatrix} -\frac{wl}{2} & 0 & 0 & 0 & 0 & \frac{wl^2}{12} \end{bmatrix}^T$

Principal of Part Locating Layout Modelling

Part assembly requires a proper location for each part/subassembly. Each set of fixture points (or PLP Principle Locating Points) of a particular part is used to determine the orientation and location of that part. Fixture points are selected as part constraints realized by tooling locators during the assembly process, as shown in Figure 4. The assumption for considering fixture points is that these points constrain parts in a specific direction in the assembly station.

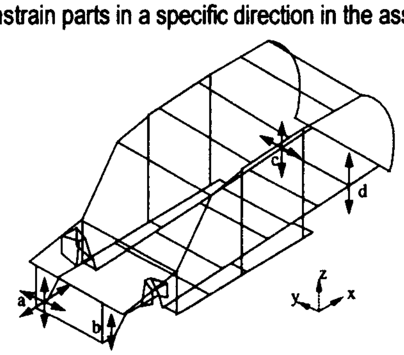


Figure 4. The locator conditions of the autobody structure.

Figure 4 shows an example in which the underbody, aperture, and roof are assembled together. For simplicity, the marked PLPs in Figure 4 show the PLP layout only for the underbody (4-2-1 locating layout). These constraints constitute a set of boundary conditions on the structure as a whole. In the structure analysis, these constraints are considered as the reduction of the stiffness matrix by the preset values on the boundaries. For example, the structure in Figure 4 has a 4-2-1 scheme to locate the structure at Points "a," "b," "c," and "d." Point a receives a six-direction control, as indicated by the six arrows. Point "c" receives a four-direction control, as indicated by the four arrows. Points "b" and "d" receive two-direction controls, as indicated by the two arrows. These points do not receive any direct applied forces but the reaction forces from the locator of the assembly stations. The constrained PLP points can be rearranged into vector $\{\Delta\}_{II}$, and the rest of the node points on the structure can be grouped into $\{\Delta\}_I$. Thus, Equation 2 becomes:

$$\begin{Bmatrix} \{P\}_I \\ \{P\}_{II} \end{Bmatrix} = \begin{bmatrix} [K]_{I,I} & [K]_{I,II} \\ [K]_{II,I} & [K]_{II,II} \end{bmatrix} \begin{Bmatrix} \{\Delta\}_I \\ \{\Delta\}_{II} \end{Bmatrix} \tag{3}$$

Because $\{\Delta\}_{II}$ is equal to zero by the definition of the PLP points, Equation 3 can be reduced to: $\{P\}_I = [K]_{I,I}\{\Delta\}_I$.

The deformation under internal loads (assembly interaction) can be calculated. Finally, Figure 5 summarizes presented methodology in the form of block diagram.

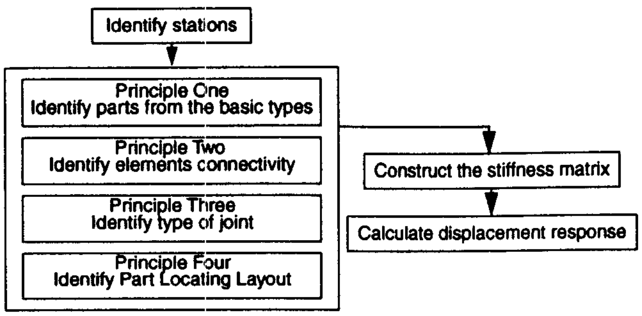


Figure 5. Summary of automotive body structure analysis.

FLEXIBLE BEAM MODEL EXAMPLE

The presented modeling approach was applied in one of the assembly plants for dimensional diagnosis of multiple faults. The present multiple failure occurred during a series of assembly processes for the side frame, underbody, and roof. This section is divided into three subsections: assembly process description, modeling, and diagnostics.

(1) The assembly process description is shown in Figure 6. It shows the assemblies that are married to the front door opening. In this assembly operation, the underbody forms the platform on which the aperture is assembled. Then, the roof components are assembled to the aperture.

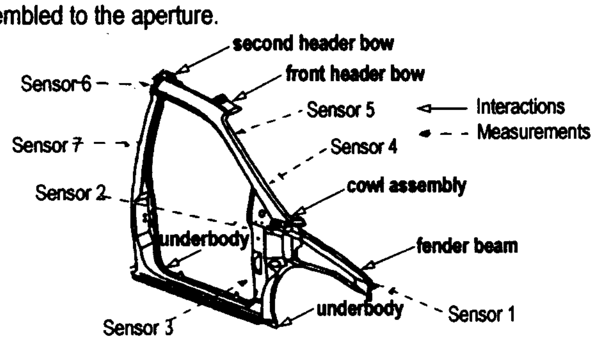


Figure 6. Assembly process for the side frame

Part-to-part interaction represents the interaction between joints caused by part dimensional deviation from nominals. Furthermorem when parts are welded together with gaps and openings between the welding surfaces, the welding process simply forces parts together simultaneously inducing forces and moments to the automotive parts. These interaction forces and moments caused by process and product faults change the final dimension of the assembly. Thus, this equalization of internal stresses introduces the correlations between some specific dimensions of the automotive body assembly which depends on the type and level of part-to-part interactions.

(2) Modeling of this process is shown in Figure 7. Using Principle 1, the frame structure is identified as the planar frame structure. By Principle 2, connectivity is identified at Joints 2, 3, 4, 5, and 6 (Figure 7). Based on the desing of assembly process of aperture and underbody, Principle 3 identifies Points 5 and 6 as the part locating layout points. Principle 4 identifies the structure forces as the interacting forces from the assembly process (welding) of the fender beam, cowl assembly, and roof bows of Figure 6. These forces act upon Points 1, 2, and 3 with 4 respectively.

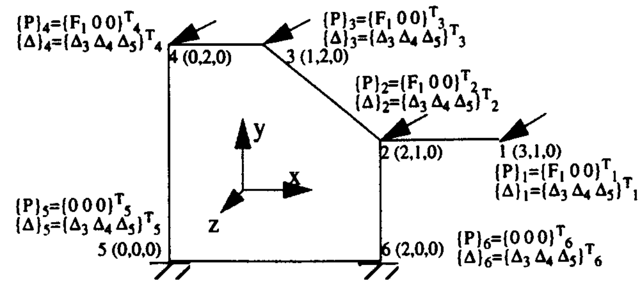


Figure 7. Structure model formulation

The displacement on each node can be calculated from Equation 4.

$$\begin{bmatrix} \{\Delta\}_1 \\ \{\Delta\}_2 \\ \{\Delta\}_3 \\ \{\Delta\}_4 \end{bmatrix} = \begin{bmatrix} [K]_{11} & [K]_{12} & 0 & 0 \\ [K]_{21} & [K]_{22} & [K]_{23} & 0 \\ 0 & [K]_{32} & [K]_{33} & [K]_{34} \\ 0 & 0 & [K]_{43} & [K]_{44} \end{bmatrix}^{-1} \begin{bmatrix} \{P\}_1 \\ \{P\}_2 \\ \{P\}_3 \\ \{P\}_4 \end{bmatrix} \tag{4}$$

(3) Dimensional control of the assembly comes from fault patterns, which are generated by simply applying forces on different locations on the structure, namely, points 1, 2, 3, or 4. These simulated responses of the structure from the interaction forces can be grouped from a series of randomly generated interaction forces. The correlation matrix can then be generated as described in (Shiu et al., 1996).

As shown in Figure 8, Fault 1 demonstrates that the cowl assembly, as described in Figure 6, is the source of the interaction forces and moments that can impact on the aperture assembly. Thus, the inconsistent cowl assembly location will cause the aperture to conform to the geometry of the cowl assembly, which causes stresses and forces that act upon the aperture assembly. Fault 2, in Figure 8, is caused by the reaction forces acted on by the fender beam of Figure 6. Fault 3 is induced by the reaction forces and moment incurred from the framer where control pads control the upper part of the aperture assembly in the framing process.

As shown in Figure 8, Faults 1 and 2 represent multiple faults that are combined with Fault 1, and Fault 2, similarly, with Faults 1 and 3 and Faults 2 and 3. Figure 9 shows the same pattern generated by the actual manufacturing dimensional measurement data. Figure 9a is caused by a combination of fault in two stations, namely Faults 1 and 2. Thus, the same pattern is generated by the dimensional failure of the fender beam and cowl assembly. A locator, which controls the location of the part that is welded to the fender load beam, was found to be missing from the operation. Installing the missing locator eliminates the variation from the fender beam. After the missing locator is installed, variation on the same sensor improved by approximately 15%.

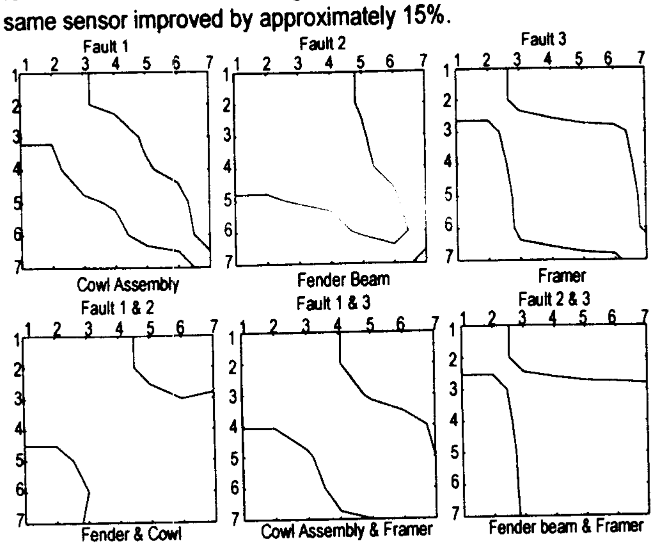


Figure 8. Single and multiple failure(s) model patterns.

Figure 9b shows the pattern after the locator was installed. Figure 9b matches with Fault 1 in Figure 8. This indicates that Fault 2 is resolved and Fault 1 shows up as the source of the failure. Fault 1 is identified as an insufficient geometrical locator in the assembly. After this insufficient locator was replaced, Sensors 1 through 7 improved from 16% to 28% in dimensional variation. This shows that multiple faults can be diagnosed with the proposed multiple fault detection scheme using the beam model. This approach emphasizes the importance of an interaction model to improve dimensional quality. The previously developed rigid body modeling (Shiu et al., 1996) could not model multiple faults due to lack of part-to-part interactions modeling capabilities.

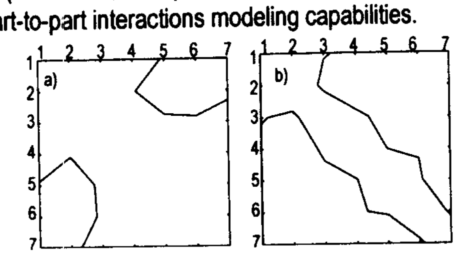


Figure 9. The actual correlation maps.

CONCLUSIONS

The complexity of modern sheet metal assembly products and processes requires early integration of manufacturing and product design during development stages. The modeling of sheet metal assembly, based on simplified geometrical principles, is an important issue for understanding design for manufacturability requirements of the design process.

This paper develops the first procedure of modeling the automotive body structure into a flexible beam structure for dimensional control of assembly process. The proposed solution, based on the simplified beam-based modeling, is generic enough to be applied to complex sheet metal assemblies, such as the automotive body, in a very early design development stage. The developed modeling approach integrates product characteristics (e.g., part dimensional variation, part-to-part joints geometry, and part flexibility) and process characteristics (e.g., parts locating schemes and assembly sequences). The integration of product and process characteristics allows for modeling of part fabrication error as well as assembly process discrepancies.

The use of flexible beam modeling in dimensional control is accomplished by the use of the following four major modeling procedures: (1) the decoupling of the automotive body into beam elements based on the functionality and geometry, (2) the beam-to-beam connectivity principle, which identifies a single beam element or a collection of beams elements connected to a single node, (3) the beam-to-beam joint geometry modeling, based on the three different basic joint types (lap-to-lap, butt-to-butt, and lap-to-butt), and (4) part locating layout in the assembly fixtures identification based on the fixture layout scheme for a given part and assembly station.

The final modeling procedure of incorporating these principles into modeling methodology for a dimensional control approach is presented. The beam-based modeling approach expands current dimensional control methods by adding flexible sheet metal parts. The developed approach was applied for dimensional control of multi-station sheet metal assembly systems with multiple fault conditions. The results of these case studies demonstrate the effectiveness of the developed beam-based modeling approach.

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