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Citation for the original published paper (version of record):
Lorin, S., Börjesson, E., Lindkvist, L. et al (2025). Simulation of Spot Welded Assemblies Using Nonlinear Shell Theory. 2nd International Conference on Highly Flexible Slender Structures.
http://dx.doi.org/10.24406/publica-5436

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Simulation of spot welded assemblies using nonlinear shell theory

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Keywords: Variation Simulation, Spot Welding, Geometrically Non-Linear Shell Theory

1. Introduction

All manufacturing processes exhibit variations from nominal settings. These variations may arise from differences in material properties, leading to geometric deviations in manufactured parts. Additionally, part variation, along with inconsistencies in fixturing and tooling, contributes to deviations in the assembly process. Such geometric deviations can cause issues during assembly or result in a decline in the functional and aesthetic quality of the final product.

Geometry assurance (GA) encompasses a series of activities throughout the product lifecycle aimed at ensuring the geometric quality of the manufacturing process. During the concept phase, design proposals are developed and evaluated in conjunction with manufacturing systems. This phase is followed by a verification stage, where inspection routines are established alongside virtual matching simulations. Finally, in the production stage, the focus shifts to process monitoring, deviation identification, and root cause analysis. The time and cost associated with design changes increase significantly as more product and manufacturing process decisions become finalized. Therefore, it is crucial to ensure that the product is highly likely to meet requirements and that those requirements are correctly defined from the beginning.

2. Locating system

Given a design proposal, the first step in GA is to develop a robust locating system. A locating system (LS) defines how a part is positioned in space using a fixture or relative to adjacent parts. It is represented as a set of triplets $(p_m, p_s, \boldsymbol{d})$, where p_m is the master point on the part, p_s is the slave point (a point on the mating surface), and $\boldsymbol{d}$ is a direction, typically the normal direction of the surface of the master point. The part is positioned by eliminating all gaps in the direction $\boldsymbol{d}$, as expressed by the equation:

$$\left(\boldsymbol{x}(p_m^i) - \boldsymbol{x}(p_s^i)\right) \cdot \boldsymbol{d} = t \quad \forall \quad i = 1, \quad \dots \quad n, \tag{1}$$

where $\boldsymbol{x}(p_m^i)$ and $\boldsymbol{x}(p_s^i)$ are the current positions of points p_m^i and p_s^i, respectively, t is the thickness of the shells here assuming the shells have the same thickness, and n is the number of positioning triplets. A robust locating system minimizes variations in key characteristics caused by deviations in the positions of the locating points $\boldsymbol{x}(p_m^i)$ and $\boldsymbol{x}(p_s^i)$. Therefore, designing a robust locating system is a key objective. From a design quality perspective, a robust locating system is fundamental, as it allows for wider tolerances.

3. Tolerance design

The next step is to define requirements for key design characteristics and assign appropriate tolerances. To achieve this, virtual tools play a crucial role in many industrial applications. These tools simulate how part variations propagate through the assembly process, ultimately affecting the final product.

Modern computer rendering also enables the evaluation of aesthetic attributes, helping to determine whether the requirements are appropriate or need adjustment. This allows designers to answer critical questions such as: Are these requirements sufficient, or do they need to be tightened or may they be widened?

4. Variation simulation

To ensure that design requirements are met and to verify that the assigned requirements are appropriate, variation simulation is used. Various techniques exist for variation simulation [1], but this discussion focuses on Monte Carlo simulation. In each iteration of a Monte Carlo simulation, deviations for all positioning points are randomly sampled based on their assigned probability distributions. An assembly function then calculates the resulting translations, rotations, and iterative adjustments based on the multi-step assembly process. Finally, deviations in key characteristics are recorded.

The finite element method (FEM) is typically used to model part deformations in variation simulations. However, Monte Carlo simulation requires solving numerous FEM models, necessitating efficient methods to handle multiple variations within a short time.

5. Spot welding

This paper focuses on variation simulation of spot-welded geometries. Spot welding is a widely used technique for joining sheet metal across various industries. In this process, a weld gun applies an electric current to heat and melt the plates, locally fusing them together to form what is known as a weld nugget. To model spot welding, linear FEM using shell elements is typically used [2] and it is often assumed that the geometric effects from heat can be neglected. The modeling steps are (1) Given initial deviations in the part and fixture, calculate the part's position and deformation by closing all positioning triplets. (2) At this stage, apply a spot weld plier to close any gap in the specified spot weld direction by enforcing the condition $(\boldsymbol{x}(s_m) - \boldsymbol{x}(s_s)) \cdot d = t$, where s_m and s_s are spot weld points. (3) While the plier forces are applied, constrain the relative position and rotation of points s_m and s_s. (4) Release the plier forces and compute the resulting spring-back effect. (5) If there are remaining spot welds, return to step (2). (6) Determine the position and deformation in the measurement fixture. To prevent geometric penetration in the modeling steps above, contact modeling is applied.

These models are typically solved using the Method of Coefficients (MIC) [3] where linear combinations of the effects from deviations are summed to model the resulting geometry. There are situations where the MIC is not ideal. For example, if a number of parts have been scanned in a pre-production series and it is necessary to model what the assembly might look like under different circumstances, it may be computationally more efficient to directly model the spot welding process without first calculating the sensitivity matrices.

6. Scope of the paper

In this paper, we have developed a model to simulate spot welding without using the standard MIC, often referred to as Direct-FEM. Using this model, we have investigated the consequences of assuming geometric linearity.

The shell model employed is based on the one proposed by Ibrahimbegovic [4, 5] and includes 6 degrees of freedom per node, including drilling rotation. The findings are used to provide recommendations on how to apply variation simulation to spot welding.

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