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NEW FEM APPROACH INCLUDING TECHNOLOGICAL PATTERNS FOR AUTOMOTIVE SPOT WELDING PARTS

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Abstract: *In the automotive industry, spot welding is one of the most productive and widespread sheet metal joining processes that benefits from a high degree of automation. To meet the increasing market demands for welded assemblies, engineers rely on virtual prototyping technologies as a comprehensive way of capturing the related underlying physics aspects. This allows for accurate welding parameters to be derived. Even so, the existing approaches achieve only a generalized structural behavior, focusing more on how the load is distributed at assembly rather than welded junction levels. The present paper combines global and detailed finite element modeling techniques that include technological patterns for simulating spot welded assemblies. The approach takes into account the effects of geometric variations occurring in the proximity of spot welds. The electrode indent is modeled by deploying variable thickness shell elements. The weld nugget is idealized by user defined cross section beams that are linked to the parts with explicit multi point constraints. The gap between the sheets is materialized by nodal offsets. Altogether, the given concepts allow engineers to achieve an accurate description of the stress and displacements at both assembly and welded junction levels. As a consequence, the cycle time of spot welding processes can be significantly lowered, considering optimal parameters and derived fixture configuration.*

Key words: *spot welding, automotive, welding parameters, finite element method, Nastran.*

1. INTRODUCTION

The European automotive market is characterized by a high degree of automation, major companies deploying flexible and reconfigurable manufacturing principles as effective ways of dealing with wide varieties of part typologies [1, 2]. To be attractive to the market, stakeholders benefit from the widespread use of Computer Aided software. This allows a synergy between virtual and physical prototyping, product adjustments being addressed from technological, economic and environmental perspectives [3, 4]. From this point of view, design decisions such as the location, number and type of assembly features have a direct consequence on process cycle time.

Spot welding is widespread in automotive manufacturing systems, being one of the most productive joining technologies [5]. The process is fully automated being performed most of the times by medium to heavy payload industrial robots equipped with specific end-effectors. Kinematic studies are widely published throughout the literature [6], being comprehensive ways of improving the performed range of movements. On the other hand, simulations based on digital mock-up software offer a valuable insight in the multiple viewports of the carried out tasks [7]. Even so, the end-effector and fixture complexity in spot welding cells is significantly influenced by derived process parameters. Welding spacing and overlap imposes tight fixture positioning constraints [8]. On the other hand, the number of squeezes, weld and hold cycles greatly influences tip wear, demanding feedback and dressing equipment to be deployed [9].

It is therefore imperative to focus on the spot welding schedules such that the complexity of manufacturing cells is minimized, while the process efficiency is maximized. Existing approaches for addressing such issues can be categorized by the involved sizing methodologies. Models based on analytical calculations and best practices derived from experimental knowledge provide the best welded nugget shear strength with respect to optimal junction stiffness characteristics [10]. On the other hand, sizing based on numerical simulation takes into account assembly conditions, achieving a good description of the load distribution [11, 12]. This allows for spot welding schedules to be decided based on more appropriate tension and shear characteristics. The multiphysics complexity of the nugget generation process can be captured by coupled simulation software [13]. Even so, such methodology is rarely deployed due to the involved complexity.

The present paper proposes a new approach for deciding optimal spot welding schedules by combining key aspects of traditional Finite Element Method (FEM) models. Technological considerations are included in the simulations such that the result accuracy is enhanced. During the welding sequence, a nugget of lenticular

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shape is generated on the overlapping area of the sheets. Existing simulation models materialize spot welds either by rigid bars or elements of circular or rectangular cross-sections. In the proposed model, flexible beams are considered having a user-defined cross section such that a shape that is closer to the real welded nugget is obtained. The applied welding pressure results in an indent around the electrode contact area.

Due to the resulting steep geometric variation, stress concentration occurs. To capture such phenomenon, variable thickness elements are deployed. On the other hand, force reactions are generated in the material due the involved thermo-mechanical effects. After the solidification of the nugget, a gap results between parts. The additional bending in the area is captured by offsetting nodes. Altogether, the given concepts allow engineers to assess both assembly and welded junction behavior such that optimal process parameters are decided. Thus, a subtle balance can be maintained between complexity and productivity.

The work is divided in four sections. At first, the automotive spot welding is discussed with emphasize on fixture design and cycle time constraints. Limiting aspects of existing methodologies for deciding parameters are derived in the second part of the work. The original contribution is highlighted in the third section, by briefly describing each technological aspect and the associated modeling approach. A case study regarding the spot welding of a car b-pillar assembly is completed in the last section. Conclusions and future work are included at the end of the work.

2. AUTOMOTIVE SPOT WELDING

Resistance Spot Welding is one of the oldest and most widespread overlapping sheet metal joining technology. The process is carried out by means of a welding gun equipped with two tongs, having attached electrode tips that exert pressure on the workpiece facilitating the flow of high density currents through the sheet contacting area. A welded nugget of lenticular shape is generated, given the combination of heat, pressure and time. Most of the spot welding processes deployed in automotive manufacturing benefit from a high degree of automation. From this perspective, a typical spot welding manufacturing cell (Fig. 1) comprises a six axis medium to high payload serial architecture industrial robot, having either a closed or opened kinematic chain (1). Its design accommodates internal or external cable dressings (2), that allow the power and cooling fluids to be supplied to a spot welding end-effector (3). Parts that are subjected to the welding process are usually located and fixed by means of semi or fully automated fixtures (4). The workspace of the robot allows all required trajectories to be generated so that the welding tips can be positioned and aligned to the sheets. Optionally, a process controller can be deployed for achieving active force feedback.

The cycle time of a spot welding process is characterized by:

$$\sum_{i=1}^{n} C_{ei} + \sum_{j=1}^{n} W_{pj} , \qquad (1)$$

where C_e is the time of each i element of the cycle (i.e. time required for robot or external positioner movements and W_p are the welding parameters deployed for each j spot (squeeze, heat, hold and off times). The two terms in Eq. (1) are in a tight relationship with the deployed welding settings (i.e. spacing, overlap region or electrode clearance) that are decided based on assembly strength, stiffness and energy absorption considerations. Thus, the goal of an optimization process is to minimize the cost function comprising welding parameters in conjunction with imposed functional and design constraints.

Assuming automotive structural elements, one way to optimize spot welding time is to lower the number of welding sequences. This can be achieved by minimizing the pitch in weld spacing, with respect to imposed safety factors. Formulations given in welding design codes recommend factor values between 1.5 and 1.6 for spot welds in shear [14]:

$$\min_{p} \sum_{j} F_{sj} , \qquad (2)$$

where p represents the pitch vector and F_s – the total shear load transferred to each j spot weld. The cost function presented in Eq. (2) can be adapted to a wide range of process parameters. For example, the weld time (cycles) can be minimized by increasing the intensity of the welding current which results in a different nugget geometry with different strength characteristics. From this perspective, an accurate description of the assembly behavior in terms of loading allows engineers to decide the best parameter configuration that can satisfy the imposed criteria with minimized cycle times and maximized process efficiency.

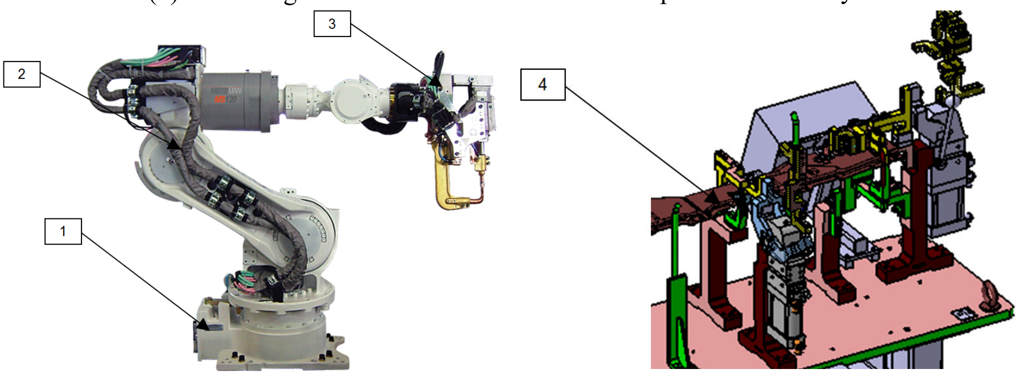


Fig. 1. Typical setup of a spot welding cell: 1 – industrial robot, 2 – cable dressing, 3 – spot welding end-effector, 4 – semi or fully automated welding fixture.

3. EXISTING APPROACHES

Spot welding is governed by interdisciplinary mechanical, electric, thermal and metallurgical aspects that describe the full dynamics of the nugget development stages. Determining the appropriate technological parameters for achieving a high quality joint can be challenging when considering that any small change in the adopted settings results in a different junction behavior. From these perspectives, three approaches can be highlighted throughout the literature and industrial practice for choosing the optimal spot welding parameters: analytical, best practice and numerical simulation ones. A brief description of them is completed in the subsections below.

3.1. The analytical approach

Formulas for a conservative definition of spot welding parameters that consider geometric, material and workpiece surface conditions are derived based on experimental data in most spot welding handbooks. The provided formulas, constants and equivalence tables are in accordance with the best achievable nugget and shear strength characteristics. Calculations use as input the thickness of the sheets *s*, derived from the sheet metal family gauge. From here, the tip diameter of the electrode d_e is approximated as [10]:

$$d_e = 4.5 \cdot \sqrt{s}\,, \tag{3}$$

or

$$d_e = 2 \cdot s + (2.5...3)\,. \tag{4}$$

Equation 3 is deployed when the thickness of the work piece is lower than 3 mm, while Eq. (4) is deployed for thicknesses exceeding this threshold. Usually, the thickness of sheets deployed in the structural automotive elements varies between 0.6 mm to 0.75 mm and 3 mm to 3.5 mm. In the next stage, the spot weld overlap region *L* is adjusted based on d_e:

$$L = (1.5...2) \cdot d_e\,. \tag{5}$$

From this step, the welding time and the intensity of the current can be decided for hard or soft welding regimes, considering the thickness of the sheet and material constants. Other parameters such as spot weld spacing are derived from equivalence tables.

The analytical approach provides the best junction strength characteristics in conjunction with the maximum number of spot welds. Even so, the high stiffness may exceed the safety factors by an unacceptable margin, proving low economical and cycle time performances.

3.2. Best practices method

In the past decades, manufacturers of spot welded assemblies have gained valuable in-house knowledge regarding the behavior of the products during their lifecycle. This allowed process adjustments to be performed resulting in guidelines, checklists and best practices derived as user accessible tabular data (Fig. 2).

Such documentation takes into account the assembly typology, possible load paths, results of non-destructive tests, unpredictable product failure, maintenance costs, as well as other critical aspects that can be used to generalize optimal technological settings. Compared to the analytical approach, the best practices method provides lower cycle times and process efficiency by considering the life cycle viewports of the product. Even so, the approach is rather approximate than accurate involving also conservative assumptions.

Part Typology	Gauge	Electrode Diameter		Spot Weld Diameter (mm)	Spacing (mm)	Weld to edge distance (mm)
		D_{max} (mm)	D_{min} (mm)			
Chasis	8	21.6	8.7	12.2	63.8	30.5
Chasis	9	20.4	8.3	11.3	58.4	28.3
Chasis	10	19.2	7.9	10.4	53.0	26.1
Chasis	11	18.1	7.5	9.6	47.6	23.9

Fig. 2. Example of a best practices table for spot welding parameters based on part typology.

3.3. Numerical simulation models

The most accurate way of deciding spot welding process parameters is to understand how the product behaves during loading, such that assembly rigidity is satisfied accordingly. In the automotive industry, simulations based on the FEM are widespread in the product design and development phase. Multiple standalone or combinations of elements are deployed such that an approximation of the load distribution is achieved at welded junction areas. Based on the level of multiphysics and modeling detail, two approaches can be distinguished.

1. *The global finite element model.* It makes use of shell elements to materialize the sheets, rigid bars, beams or multi point constraints (MPC) being deployed to achieve a simplified representation of the weld nugget and its interaction with the parts. Load cases are defined corresponding to different scenarios that occur during the life cycle of the vehicle. Based on the imposed displacements and boundary conditions, stress and force reactions are calculated for each part and junction element. Extraction of the nodal forces can be performed for spot weld elements, such that the tension and shear loads are evaluated. Junction safety factors take in to account the gauge and the geometry of the nugget. Spot welded gauge 18 mild steels can withstanding up to 2.3 kN loads in shear. Figure 3 depicts examples of beam and hexahedral elements that are used to materialize spot welds in a two component junction. The global finite element model provides a reasonable description of the load distribution at assembly levels. Even so, certain technological aspects of spot welding are idealized, a coarse level of detail being reached at the junction sheet interaction area.

2. *The detailed finite element model.* Compared to the global model, the detailed model deploys exclusively 2D or 3D elements to model the nugget with a high level of

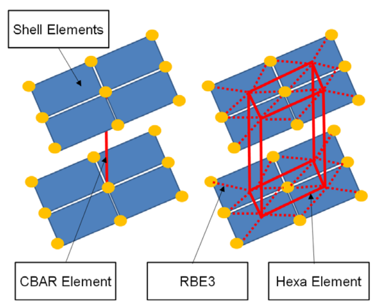


Fig. 3. CBAR and RBE3 – Hexa Spot weld representations.

mesh refinement. Simulation of the current flow is carried out to evaluate Joule heating effects. Thermal analysis is deployed to study the distribution of temperature and heat fluxes. Date and birth of elements can be activated to capture the nugget generation process. Stress and deformations resulting from the coupled effect of all analyses are transferred to static structural modules.

The numerical models provide a more accurate description of the load distribution at junction areas than compared to the other approaches. Even so, the high level of detail involved in global finite element models demands high computational costs which make such simulations attractive only to research and academia rather than automotive manufacturing.

4. A NEW APPROACH

The dynamics of the spot welding process results in indents, gaps and uneven geometric features that can have severe consequences on the load distribution resulting in local stress concentration. To capture the behavior imposed by such technological patterns, the proposed approach combines aspects of the global and detailed finite element models. In this way, a subtle balance is maintained between computational demands and result accuracy.

In the first stage, the thickness variations in the electrode contact area are captured by delimiting a region of shell elements that encompass the diameter of the nugget. Mesh refinement is performed for this patch to increase the results accuracy. The element properties cards are updated such that the thickness in the delimited region takes into account indentation. Values corresponding to these effects can be extracted from the literature, based on the type of material and deployed process parameters [15].

After the welding solidification phase, a small gap results between the components. Assuming that the nugget behaves as a beam, an increase of the bending moment is expected when the junction is subjected to shear loads. To take into account this effect, the nodes corresponding to the two sheets are offset. This displacement excludes the shell thickness effects imposed by mid-surfacing.

In all existing approaches, the nugget is materialized either as a rigid bar or as a flexible circular or rectangular cross-section beam. In practice, the lenticular shape of a spot weld induces a different cross section behavior. From this perspective, flexible beams are added to model lenticular cross-section beams having user-defined centroid, area, moment of inertia, section modulus and radius of gyration. Explicit MPC link these elements to the surrounding model.

Figure 4,*a* depicts a schematic representation of the proposed approach while Fig. 4,*b* illustrates an example of normal stress gradients occurring for two spot welded sheets with extra details for visualizing the FEM representation. The clear effect of stress concentration due to the technological patterns can be observed.

5. SPOT WELDED CAR B-PILLAR

A case study is completed in this section to prove the given concepts for a car B-pillar (Fig. 5). The assembly

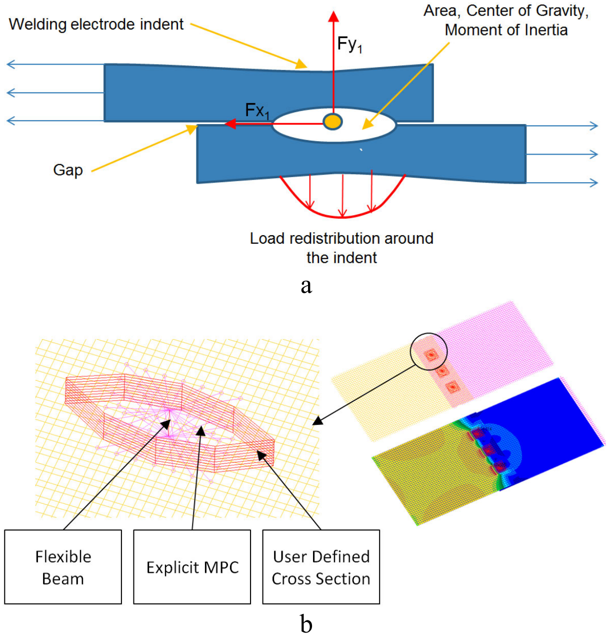


Fig. 4. The proposed approach: *a* – schematic representation; *b* – FEM model and normal stress distribution.

consists of two sheet metal bodies that are spot welded to enhance impact safety. Quenched and tempered alloy steel 18 gauge ASTM A709 is used (corresponding to 1.27 mm equivalent thickness) for both parts hinges for the front and rear doors that are mounted to a reinforcing plate using high strength shear bolts. The design is inspired from [16].

The study provides an insight in the process cycle time optimization by means of static analysis. The spot weld spacing is increased and subsequently the number of points decreases. Modal, frequency response, fatigue and impact criteria are neglected. The loads applied are the own mass of the front and rear doors in the hinges. Enforced displacements are defined in the pillar – chassis interaction area such that the effect of the vehicle movement for different type of terrains is considered. Three load case that provide worst case scenarios are chosen for the analysis. The 3D model is processed with MSC Patran, resulting a 2D shell structure. The computation is performed using MSC Nastran. Details regarding the geometry, spot welds, mesh, as well as the total number of elements and nodes are presented in Fig. 6. Dimensions are also presented to provide an overview of the model scale. To capture the behavior of the shear bolts CBUSH elements are defined.

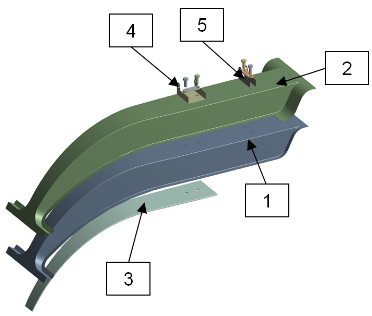


Fig. 5. Assembly of the car B-pillar: 1 and 2 – interior and exterior sheet metal bodies, 3 – reinforcing plate, 4 and 5 – hinge supports.

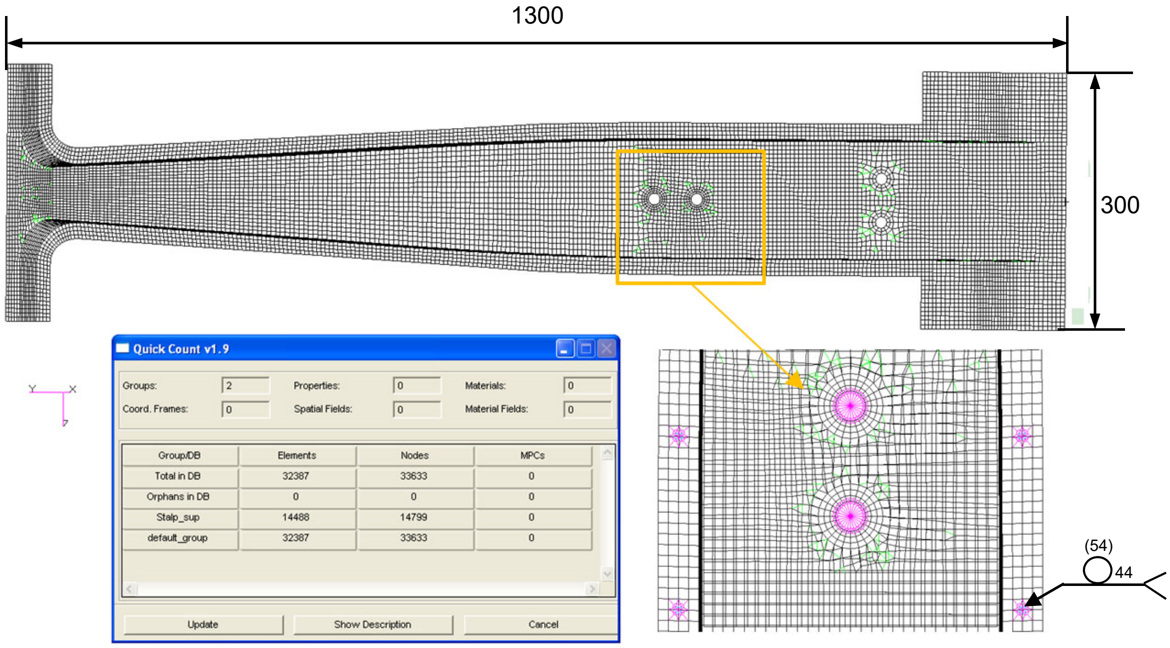


Fig. 6. Details regarding the geometry, mesh, number of elements and nodes, as well as the definition of spot welds and shear bolts.

In the first stage of the analysis, the best practices method is deployed to decide baseline spot welding spacing and nugget geometry. The initial configuration comprises 108 weld points. Equivalent stress and junction safety factors are evaluated at assembly and junction levels. Shear and tension force extractions are carried out considering that each beam has an individual coordinate frame, where the *XOY* plane is aligned normal to the sheets, the *Z* axis pointing along the element.

To optimize the initial configuration, a session file is defined in Patran to allow a parametric adjustment of the spot welding pitch based on user defined commands. Only minor mesh improvements are required in the sheets overlapping area so that the connectivity between the beams and shells can be satisfied without a high level of MPC or shell element distortion. For each new configuration, a Nastran input file is generated.

The target of the parametric analysis is to identify the maximum allowed pitch that can satisfy all imposed criteria. Figure 7 depicts the Von Misses stress results achieved for the initial 108 weld points, side by side with the optimized 34 weld points configuration. A clear overview of the load distribution effects in the structure is achieved. In the initial configuration, the assembly has a high stiffness in the overlapping area of the sheets. The maximum Von Misses stress has a magnitude of 59 MPa, being located in the right side of the image. The junction safety factor is greater than 5, meaning that the applied loads can increase by 5 times for the junction to lose its structural integrity. As the number of spot welds was decreased, the stress gradients migrated, meaning that a lower amount of the applied load is transferred to the overlapping area. This result in a slight increase of the stresses, the maximum equivalent Von Misses stress being 65 MPa, localized around the mounting hole of the upper hinge. The junction safety factor has decreased to 2.5, which can be considered satisfactory in both terms of structural safety and process efficiency (considering the value of 1.6 recommended by the welding design code). Information regarding the three subcases defined in the analysis is presented in Table 1. Figures 8,*a* and *b* depict the stress and shear load safety factor variation for each pitch adjustment loop.

Altogether, the simulations managed to realistically capture the static behavior of a spot welded assembly, taking into account a full range of technological patterns (electrode indent, cross-section of the nugget, gap between parts and distribution of tension / shear loads considering worst case scenario load cases) such that the optimal process parameters can be derived. As a consequence, the complexity of the welding fixtures can be lowered while cycle times can be enhanced.

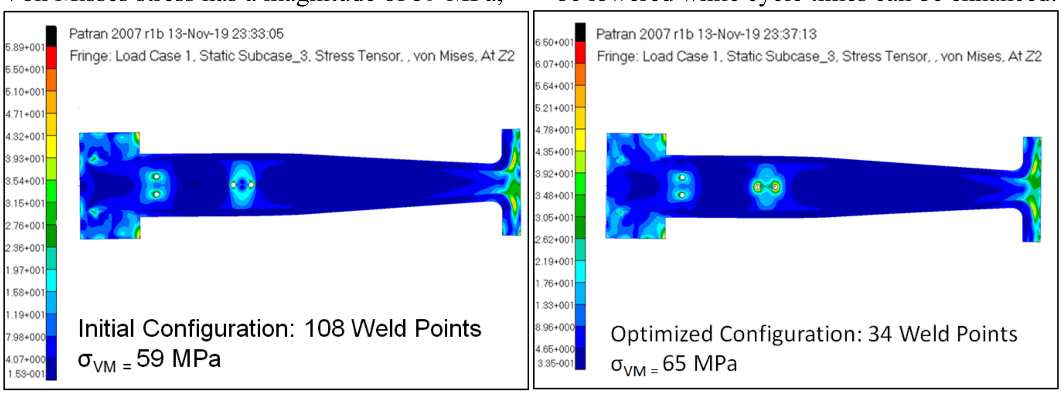
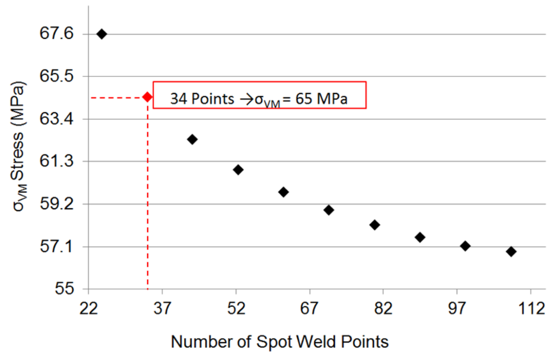


Fig. 7. Equivalent Von Misses stress for the initial and the updated configurations.

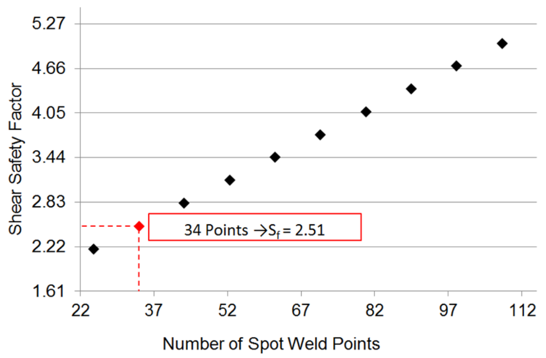
Table 1

Simulation Parameters

Subcase ID	Hinge Support Loads (N)			Upper and Lower Displacements (mm)		
	Fx	***Fy***	***Fz***	***Dx***	***Dy***	***Dz***
1	98	−451	50	0	−0.11	0.09
2				0	0.18	−0.1
3				0	0.22	−0.12



a



b

Fig. 8. Relationship between the number of spot weld points and: *a* – equivalent Von Misses stress (MPa); *b* – shear safety factor.

6. CONCLUSIONS

The present paper has addressed the limiting aspects of spot welding parameter estimation methodologies, with emphasize on assemblies used in the automotive industry.

A new approach was developed involving the use of flexible beams for defining the real spot weld geometry, variable shell thickness elements for capturing electrode indentation effects, as well as nodal offset for increasing bending moments due to geometric gaps.

A case study was completed to illustrate the given concepts for a B-pillar structure. By adding technological patterns into the simulation model, a realistic load distribution was achieved, allowing the stress and safety factors to be captured with a high level of detail.

The parametric study reduced the number of the spot welds by considering only static criteria. As a consequence, the cycle time can be optimized by limiting the range of movements performed by the industrial robot, as well as the complexity of the welding fixtures.

Future work will focus on developing more generalized FEM techniques such that the definition of the model and parametric analysis can be performed with a minimalistic user input.

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