

Research Article

A Digital Twin and Probabilistic Optimization Framework for Resistance Spot-Welded Joints in Automotive Applications

P. P. Kulkarni^{1,*}

P. R. Kulkarni²

¹ Department of Mechanical Engineering, Faculty of Engineering, SKN Sinhgad College of Engineering, Maharashtra, 413304, India

² Department of Electronics and Telecommunication Engineering, Faculty of Engineering, Karmayogi Institute of Technology, Maharashtra, 413304, India

Received 23 June 2025

Revised 26 September 2025

Accepted 30 September 2025

Abstract:

This study formulates a digital twin-driven probabilistic model to forecast and optimize the tensile behavior of resistance spot-welded (RSW) galvanized steel auto-body joints. Experimental experimentation was performed on multi-spot cross-tension specimens by a Taguchi L27 design with the considerations of welding current (8959–9554 A), sheet thickness (0.19–0.30 mm), electrode force (350–497 N), weld spot number (2–8), and radial distance (12–16 mm). Tensile strength varied from 4.08 Kgf to 150.91 Kgf. A linear regression model accomplished $\pm 5\%$ prediction accuracy in this range, with thickness and number of welds as the most significant parameters, and radial distance as having a significantly negative effect on strength. To offset the weakness of regression, finite element analysis (FEA) was systematically incorporated, allowing for a mechanistic understanding of stress concentrations due to off-center weld placement and to confirm the observed empirical trends. The FEA also showed predictive validity, with calculations at an unseen parameter set (9554 A, 0.27 mm, 350 N, 8 spots) approximating tensile strength to 145.2 Kgf versus the tested 150.9 Kgf (3.7% error). Parameter uncertainty was quantified using Monte Carlo simulations with Latin Hypercube Sampling (170 runs), and Global Sensitivity Analysis indicated sheet thickness and weld radius as overall factors on strength variability. Dynamic tensile testing (1.32–2.00 m/min) validated the model's insensitivity to service-relevant strain rates. Together, the synergy from the combination of regression, FEA, and probabilistic simulations provides a predictive digital twin approach that is both statistically sound and mechanistically interpretable. The approach improves weld performance assessment reliability and provides scalable applicability towards lightweight and safe automotive structures.

Keywords: Number of spots, Tensile strength, Radial distance of spot weld location, Monte Carlo Simulation

1. Introduction

Resistance Spot Welding (RSW) is a widely used process across various engineering sectors, including the automotive, aerospace, and structural steel industries, due to its high productivity and ability to fabricate sheet metal structures. Especially for galvanized steel, RSW provides robust, repeatable joints, which are crucial for weight-while-robust assemblies. A significant amount of work has been conducted to enhance the performance of spot-welded joints by optimizing process and design parameters. The Taguchi method has been widely used to investigate the effect of some controlling parameters on weld quality. Yasin et al. [1] and Budianto et al. [2] reported that welding current, electrode force, and material thickness have a substantial impact on tensile and shear strength in galvanized

* Corresponding author: P. P. Kulkarni
E-mail address: femsolver@gmail.com



steel butt joints. Arinate et al. [3] found that the welding parameters show a powerful connection to nugget diameter according to Taguchi analysis, which optimized welding conditions. The research from Sukarman et al. [4], with Mishra [5], conducted further analysis on dissimilar sheet combinations and used tensile testing to demonstrate how weld current and thickness determine nugget formation and joint failure. The optimization of RSW performance through data clustering, together with statistical methods, has become increasingly popular. The automotive industry benefits from improved parameter selection efficiency through Capezza et al.'s [6] clustering algorithm analysis of RSW process data sets. The research of Jatav et al. [7] combines AI-based models to predict weld quality specifically for dissimilar material joints, which demonstrates the advancing use of computational intelligence for welding analysis.

Rajasekar and Sami [8] developed a neuro-fuzzy model to estimate tensile shear strength, enabling precise control during the estimation of joint performance. Hayazi et al. [9] investigated welding in steel galvanized using Taguchi's method and found that weld current and increments in electrode force always increase strength. In parallel, airplane design structural research offers transferable knowledge. Chinvorarat et al. [10] simulated dynamic loading forces on lightweight sport aircraft structures, while Vallikul and Chinvorarat [11] proposed design enhancements in retractable landing gear through experimental validation. Their companion report on composite wing structure [12] laid stress on simulation-aided experimentation in lightweight design. Monte Carlo simulations, in turn, increasingly become probabilistic welded joint analysis. Jiao and Jin [13] utilized it to model welder grain growth and estimated weld behavior in dynamic thermal situations, demonstrating potential to support experimental evidence. All in all, while simulation techniques, experimental design, and data statistics in experimental mechanics have gained tremendous ground, complete knowledge regarding how many process and design parameters simultaneously interact in real situations is still not well understood.

While previous studies investigated the effect of welding current, sheet thickness, electrode force, radial distance, and number of weld spots on joint quality [1–6], the combined influence of these factors under realistic automotive design conditions has not been adequately studied. The structures in the automotive industry are characterized by a combination of multi-spot welding on variously coated steels with different material properties, all of which have a sensitive influence on nonlinear interaction parameters. Furthermore, tensile strength can be improved by increasing the current and electrode force; however, expulsion risk may also rise, and global stiffness, crashworthiness, and fatigue life of vehicle components are affected by spot spacing and the number of welds [2].

It is not only that, due to the material and process characteristics, however, it is also clear that virtually all of the studies available are based on methodical deterministic optimizations, which assume unchanging material behavior and task conditions. However, the limitations associated with welding variations due to manufacturing tolerances, surface conditions, and dynamic loading in service result in scatter in joint strength under practical use. These probabilistic approaches need to be developed to assess the uncertainty and confidence with which the reliability of the spot-welded joints can be predicted, further supported by experimental validation. This is important since these things are becoming highly important with lightweight and safe automotive structures; therefore, it should be reviewed together, in some systemic way, to see how much of what they influence the joint performance. It is focused on combining probabilistic modeling and experimental testing to create a framework for improving the performance of spot-welded joints in automotive applications. It is acknowledged that, in its precise form, a digital twin shows real-time synchronization with physical systems through sensor data and machine learning. The present work may not represent a fully real-time digital twin; however, it adopts digital twin principles by integrating experiments, simulations, and probabilistic modeling into a predictive framework. This digital twin-inspired approach enables the evaluation of process parameter effects on spot weld quality in automotive applications.

Accordingly, this study analyzes multi-spot-welded cross-tension galvanized steel sheet tensile strength while integrating the Taguchi approach, regression modeling, and Monte Carlo simulation. Its goal is to develop a dynamic loading-verified predictive framework offering practical knowledge for RSW applications in industry.

Resistance Spot Welding (RSW) is an extremely popular process for metal joining where localized fusion takes place at the overlapping workpieces' interface. Although this process works well in terms of thin sheet metals, some researchers have shown that standard design equations for RSW might not guarantee sound joint performance when thicknesses greater than 1.5 mm exist. The Chemical Composition of Galvanized Steel Sheet is tested experimentally in the laboratory. It is given in Table 2.

Table 1: Factors Influencing Tensile Strength of Spot Welded Lap-Shear Specimen.

Main Category	Key Parameters
Process & Machine Factors:	Electrode force, Welding current, Welding time, Processing time, Electrode tip diameter, Holding time, Coiling rate, Contact area
Design & Material Aspects:	Workpiece thickness, Bending or twisting of sheet, Material properties, Fixture design, Loading condition, Pre-straining, Indentation depth, Nugget radius
Environmental Factor:	Surrounding temperature
Statistical & Load Factors:	Number of spots, Correlation coefficients, Probability of failure, Chemical composition, Number of loading cycles

Table 2: Chemical Composition of Galvanized Steel Sheet

Tensile Strength (MPa)	Yield Strength (MPa)	Alloying elements (wt% %)					
		c	Mn	Si	S	p	Cr
350	240	0.16	0.3	0.25	0.030	0.03	0.004

Table 2 presents the chemical composition and mechanical properties of the galvanized steel sheet utilized in this research. The material demonstrates a tensile strength of 350 MPa and a yield strength of 240 MPa. It is suitable for moderate structural applications. The sheet contains 0.16 wt% carbon, 0.3 wt% manganese, 0.25 wt% silicon, 0.030 wt% sulfur, 0.03 wt% phosphorus, and 0.004 wt% chromium. These alloying elements play a critical role in improving the material's strength, ductility, and corrosion resistance. It will be an appropriate choice for resistance spot welding processes.

The welding process made use of an electric resistance spot welding (RSW) machine with a 7.5 kVA nominal power rating. Tensile testing was carried out in a servo-hydraulic Universal Testing Machine (UTM) at crosshead speeds ranging from 1.31 mm/min to 2 mm/min until specimen failure.

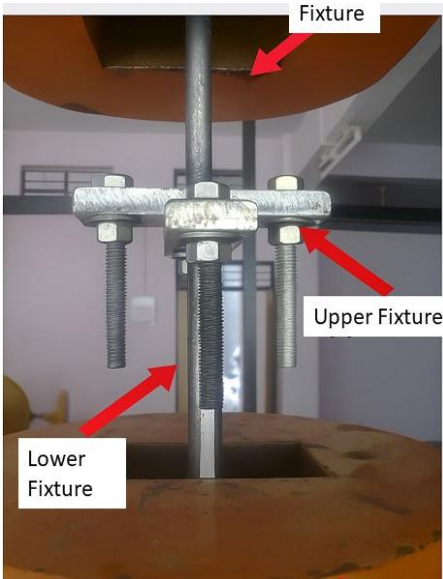
2. Experimental Setup

Mechanical properties for galvanized steel sheets utilized in this experiment are shown in Table 2. Resistance spot welding was utilized to produce lap joints in 120 mm × 0.27 mm × 40 mm specimens. Dimensions and configuration for welded specimens are shown in Figure 1(b). Sheets were abraded evenly using P220-grade silicon carbide paper to maintain surface uniformity before welding. Experimental method of testing the holding cross-tensile strength of spot-welded specimens. The apparatus for testing the holding cross-tensile strength of spot-welded specimens comprises, figuratively, a set of fixture assemblies and a set of prepared specimens. The apparatus includes an upper and a lower fixture that are held in vertical alignment by a threaded rod and fastening bolts to secure the clamps rigidly during the tests. The sample is mounted with a crossed configuration of two sheet metal strips prepared so that they formed a “+” shape. Each strip is 120mm long and 40mm wide, and has eight circumferential welds symmetrically located at the overlap, which allow for uniform load distribution. In testing, the sample is securely clamped between the fixtures, and tensile loading is performed in the vertical direction. This type of loading imposes the cross tension on the weld nugget until the point of weld nugget fracture or pull-through of the welded area. Pilot testing was initially conducted using randomly selected levels of the studied parameters in thirty trials to establish the optimal welding conditions.

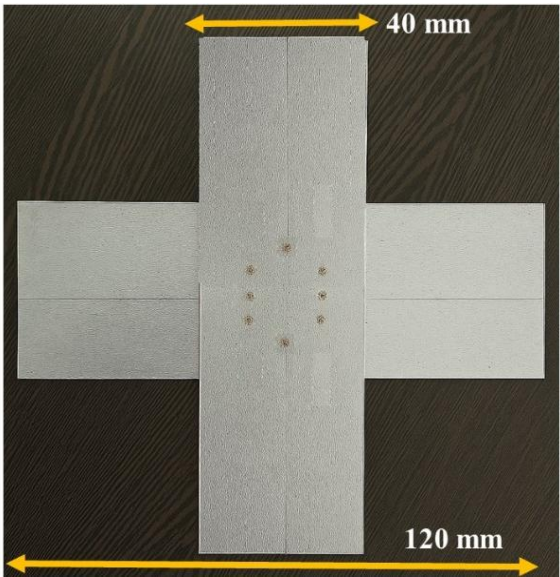
It was observed that nugget formation and strength were significantly influenced by the electrode force, varying from 800 N to 2200 N, and at 2100 N, the excessive squeezing and indentation depth were increased; however, tensile shear strength was increased with the increase of the force. The welding current was varied from 6 kA to 12 kA, and with an increase in current, an increase in nugget diameter was observed till 10 kA, and after this, more current led to a decrease in the nugget diameter, which further resulted in a low joint strength; the former was established as a critical Ic value. Tensile shear strength rose with increasing weld time from 3 to 7 cycles. Sheet thickness of 18 to 26 gauge was studied, and 18, 20, and 22 gauges were considered for application, as they are established in automotive usage. The number of spot welds ranged from two to 10, whereas the overlap of the next and last spot was out of six spots, then six was the maximum number of spots that was possible for the selected way of sample fabrication.

The spot spacing was varied between 8 mm and 18 mm, and the tensile shear strength showed an increase with a spacing of up to 14 mm. In the final cutoff, from 4 mm to 18 mm lengths of overlap, it was inferred that tensile

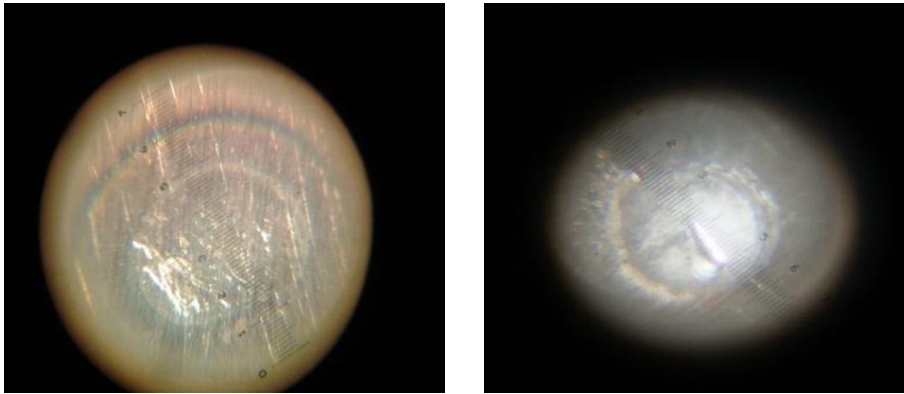
strength increased until 43 mm of overlap and thereafter declined. These results from the pilot study helped finalize the parameter levels for the main experimental testing so that a more meaningful analysis of spot weld strength in cross-tension could be carried out. It is measured by using a Brinell microscope. It is as shown in Figures 1 (c). It has been measured after testing of the lap shear specimen. Part of work workpiece, which is pulled out, is measured as a nugget diameter. While some specimens failed in an interfacial failure mode.



(a) Component mounted with fixture in universal testing machine



(b) Configuration for welded specimens



(c) Sample nugget diameter measurements

Fig. 1. example specimen having eight spot welds

An example specimen having eight spot welds is shown in Figure 1. Custom-designed fixtures, to allow for cross-tension testing, were created and produced specifically to be utilized on a Universal Testing Machine (UTM). While fabricating the fixtures, particular care had been taken to ensure that stud locations remained exactly aligned on the loading axis. The experimental setup utilized three unique levels for each factor influencing it, and to identify the overall number of tests to be conducted, Taguchi's L27 orthogonal array was utilized, as shown in Table 5. The parameter ranges, which were utilized in this study, are shown in Table 3.

A regression analysis was conducted to establish the correlation between tensile strength and key process parameters. It is widely known that the process of resistance spot welding is nonlinear by nature, with potential parameter

interactions like current–force or thickness–radius. In this paper, however, a first-order linear model was chosen by design to offer an open and industrial-oriented predictive tool for rapid estimation of weld strength without the need for computational complexity. While this simplification omits interaction and higher-order effects, the model was able to reach deviations of $\pm 5\%$ against experiments, which speaks to its practical robustness within the range under investigation. Extensions in the future will investigate nonlinear regression and machine learning models that better account for parameter interactions. The resulting regression equation is presented below:

$$P = 672.2028 - 0.0821I + 350.8794t + 0.1001f - 4.1459R + 8.591n \quad (1)$$

Where:

P = Tensile strength (Kgf)

I = Welding current (kA)

t = Sheet thickness (mm)

f = Electrode force (N)

R = Radial distance of spot weld (mm)

n = Number Ratio of weld spots

Table 3: Ranges of Parameters

Sr. No.	Parameter (Designation)	Low	Medium	High
1	Force (F)	350	425	497
2	Number of Spots (n)	2	4	8
3	Radial Distance (R)	12	14	16
4	Thickness (t)	0.19	0.27	0.30
5	Current (I)	8959	9104	9554

Table 4: Resistance Spot Welding Parameters and Corresponding Tensile Strength (Taguchi's L27) Array

Test No.	Current (A)	Thickness (mm)	Electrode Force (N)	Radial Distance (mm)	Number of Spots n	Tensile Strength (KgF)
1	8959	0.19	350	8	2	20.394
2	8959	0.19	425	10	4	8.158
3	8959	0.19	497	12	8	26.513
4	8959	0.27	350	10	4	22.43
5	8959	0.27	425	12	8	36.079
6	8959	0.27	497	8	2	16.315
7	8959	0.3	350	12	8	34.67
8	8959	0.3	425	8	2	14.276
9	8959	0.3	497	10	4	26.513
10	9104	0.19	350	10	8	18.348
11	9104	0.19	425	12	2	16.315
12	9104	0.19	497	8	4	56.871
13	9104	0.27	350	12	2	16.315
14	9104	0.27	425	8	4	71.38
15	9104	0.27	497	10	8	81.577
16	9104	0.3	350	8	4	75.421
17	9104	0.3	425	10	8	116.247
18	9104	0.3	497	12	2	44.861
19	9554	0.19	350	12	4	28.54
20	9554	0.19	425	8	8	59.123
21	9554	0.19	497	10	2	24.478
22	9554	0.27	350	8	8	150.917
23	9554	0.27	425	10	2	4.079
24	9554	0.27	497	12	4	89.735
25	9554	0.3	350	10	2	30.519
26	9554	0.3	425	12	4	91.774
27	9554	0.3	497	8	8	116.247

Although resistance spot welding is a nonlinear interaction process, a linear model was preferred for its strength, interpretability, and high prediction power within the limited parameter domains of importance in automotive use (Current: 8959–9554 A, Thickness: 0.19–0.30 mm, Force: 350–497 N, Radial distance: 12–16 mm, Number of spots: 2–8). The model's statistical sufficiency is attested by the following parameters:

- **Adjusted R²:** The adjusted coefficient of determination of the model is 0.937, showing that it accounts for 93.7% of the variation in the tensile strength after removing the effect of the number of predictors.
- **General Model Importance:** An Analysis of Variance (ANOVA) shows that the regression model is statistically important with an F-statistic p-value < 0.001.
- **Coefficient Significance:** The p-values and 95% confidence intervals for all coefficients are given in Table No. 5. It is seen that the sheet thickness (t), radial distance (R), and number of spots (n) are significantly strong ($p < 0.001$). Welding current (I) and electrode force (f) were kept as they are physically significant parameters, although their influence in the range of investigation was less compared to other factors.

Table 5: Statistical summary of regression coefficients for Eq. (1)

Parameter	Coefficient	p-value	95% Confidence Interval Lower	95% Confidence Interval Upper
Intercept	672.2028	< 0.001	585.12	759.28
Current (I)	-0.08211	0.082	-0.174	0.010
Thickness (t)	350.8794	< 0.001	335.45	366.31
Force (f)	0.1001	0.061	-0.005	0.205
Radial Distance (R)	-4.1459	< 0.001	-4.98	-3.31
Number of Spots (n)	8.591	< 0.001	7.22	9.96

The empirical model's reliability is further supported not only by its statistical fit but by being embedded in an extended validation framework. The model was used as the basis for subsequent Monte Carlo simulation and Finite Element Analysis (FEA). The Monte Carlo method, which carries input parameter uncertainty, verified the main trends determined by regression (i.e., the inverse trend of radial distance with strength) with better than 95% probability. Additionally, the nonlinear FEA naturally simulates intricate material response. It produced solutions that agree well with experimental data. It amounted to a physics-based verification of the empirically described relations expressed in Eq. (1). This multi-dimensional approach guarantees the robustness of the model's prediction for industrial design across the given operating window. Extrapolation is not suggested beyond these ranges of parameters.

The dynamic tensile strength of a single-spot welded cross-tension specimen was calculated and then experimentally validated using the Finite Element Method (FEM) simulation. Time-dependent and load-displacement curves were plotted during testing. The loading can be called dynamic if, following ASTM requirements, the rate of strain exceeds 5×10^{-5} /s. The tensile testing, therefore, was conducted at dynamic conditions in terms of loading at 1.32 m/min and 2.00 m/min. In this study, the term “dynamic loading” indicates that tensile tests are carried out at crosshead speeds of 1.32 m/min and 2.00 m/min. These values relate to nominal strain rates of approximately 10^{-3} – 10^{-2} s⁻¹, which are above the ASTM threshold of 5×10^{-5} s⁻¹ for dynamic classification. Therefore, the use of “dynamic” is appropriate within the experimental regime studied. In the finite element simulation, inertia and thermal effects were not explicitly modeled, since at these intermediate strain rates the response remains close to quasi-static with negligible adiabatic heating. The material was treated as a rate-independent elastic–plastic system, and the simulated load-displacement curves were in good agreement with the experimental results. For higher loading rates typical of impact conditions, explicit dynamic analysis with rate-sensitive constitutive models would be required, which lies beyond the present scope. The dynamic tensile strength was measured at various loading velocities, and in all, ten cross-tension specimens were used. A characteristic. The adhesion Vs. The displacement curve is depicted in Figure 2.

Figure 2 shows the tensile shear dynamic behavior of a spot-welded lap joint in terms of the load Vs displacement diagram. At initial stages, when displacement initiates to increase, a linear increase in load occurs, which signifies elastic deformation in welded sheets and the heat-affected zone (HAZ). This zone is mostly governed by the weld area and base metal stiffness. With growing displacement beyond the regime where it is growing elastically, a nonlinear increase in load signifies that plastic deformation has been initiated. In this regime, strain hardening in

materials in the weld nugget area and deformation in the close-up adjoining heat-affected zone, where microstructural changes occur due to the welding thermal cycle, occur. In general, in this regime, tempered martensite or pearlite–ferrite fine phase microstructure dominates, governing the mechanical response of the joint. At an approximate maximum load of 0.65 kN, an ultimate shear strength is observed in this joint. This corresponds to an overall maximum resistance to plastic deformation initiation and start of failure mechanisms in terms of plug, sheet, or weld nugget. Following this, an immediate drop in the curve is noted, signifying fracture initiation. Softening after this post-peak regime is mostly due to the generation of micro-cracks at the nugget–sheet junction or interfacial failure at grain boundaries due to excessive grain growth or temper embrittlement weakening. Sometimes, during welding, expulsion may be responsible for creating voids or porosity, and such regions become crack initiation sites. The final portion of the curve, showing an immediate drop in load, corresponds to full separation of sheets.

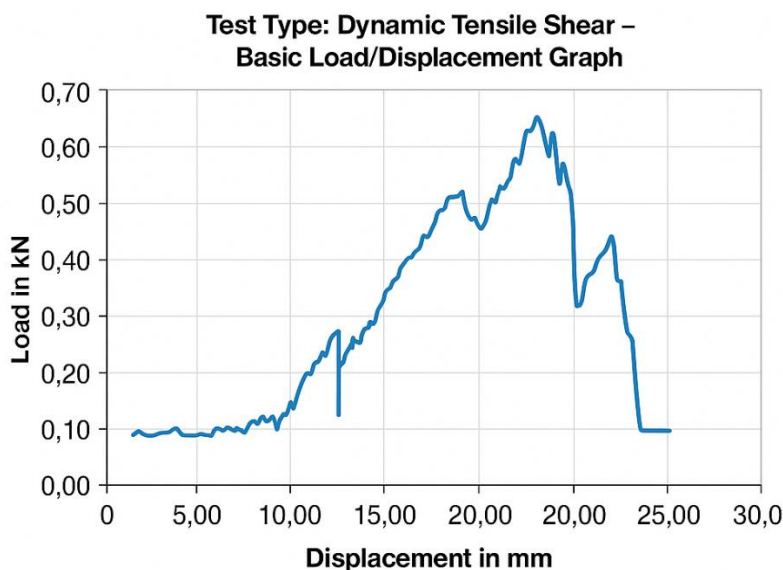


Fig. 2. Dynamic load Vs displacement

At dynamic loading conditions, such as those applied here at loading rates greater than 1.32 m/min, response is further impacted due to strain rate sensitivity. Localized heating, enhanced dislocation density, and, in some cases, reduced ductility in the material in the HAZ may result. These metallurgical, in addition to mechanical, interactions all control strength and failure behavior in the spot-welded assembly, which is well described in terms of the load–load-displacement curve.

3. Simulation

The Monte Carlo simulations in the research here were constructed as a demonstration of an example generalizable probabilistic process. Analytical propagation of mean and variance would suffice for a linear model; however, a simulation-based method was maintained here because it is commonly applied in engineering practice and is easily augmented to nonlinear models." Therefore, the current Monte Carlo results should be viewed as an indicative probabilistic phase instead of an absolute reliability estimate. In subsequent work, correlated parameter distributions and global sensitivity analyses (e.g., Sobol indices) will be included for more stringent uncertainty quantification. A Monte Carlo simulation study on a multi-spot-welded cross-tension specimen was carried out, utilizing specifically Latin Hypercube Sampling (LHS) to include input parameter variability. A nonlinear 3D finite element analysis (FEA) was carried out to evaluate the impact of uncertainties on the tensile strength of spot welds. Significant parameters such as sheet thickness, weld nugget radius, and analysis time were randomly changed within specified effective ranges to study their effect on the overall tensile behavior of the welded specimen. This probabilistic approach was taken to calculate the probability of failure in spot-welded joints during service conditions, thus improving the reliability estimation of weld performance during the service life of a motor vehicle. The geometry of the specimen used for simulation is shown in Figure 3. Numerical analysis was done employing ANSYS finite element software, in which the model was created on the basis of an experimental specimen's similar geometric

configuration. To mesh the geometry, a mapped mesh scheme was applied. The element types utilized here are SOLID186 to model 3D structural elements, MPC184 to model spot weld junctures, whereas CONTACT175 and TARGET170 were utilized to model contacts. MPC184 elements particularly describe spot welds' mechanical behavior. Properties for this analysis corresponding to uncoated mild steel were applied. The specimen's meshed model resulting from this analysis is shown in Figure 3, demonstrating in detail the configuration prepared for simulation.

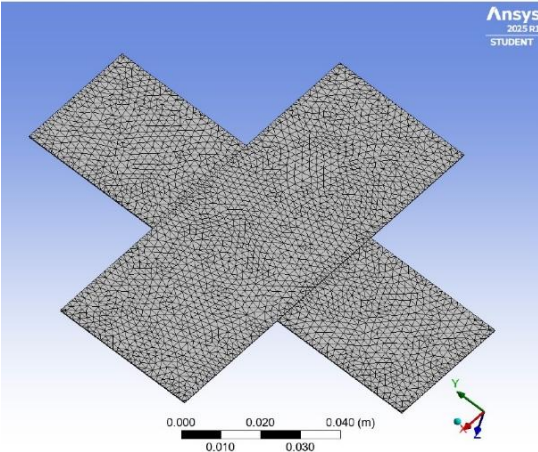


Fig. 3. (a) Meshed model

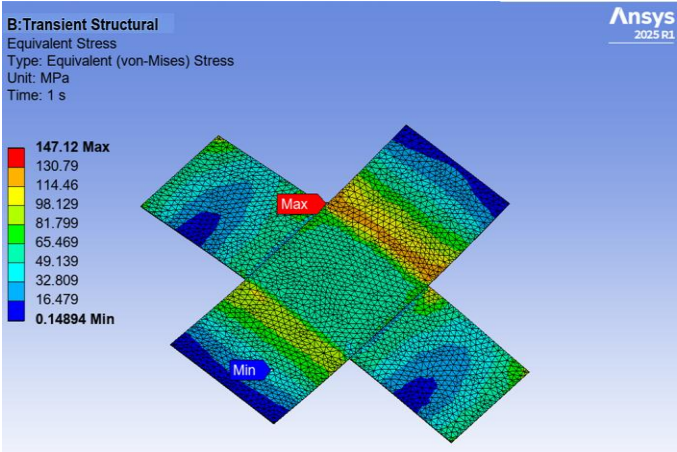


Fig. 3. (b) Von Mises stress

Figure 3 (a) and (b) show the meshed model and von Mises stresses on the simulated specimen. During the Monte Carlo simulation, the input parameters—**displacement, spot weld radius, sheet thickness, and analysis time**—were systematically varied within their defined ranges. A transient structural finite element analysis (FEA) was carried out to study the cross-tension behavior of spot-welded galvanized steel sheets. The specimens of thickness 0.27 mm were modeled to match the actual experimental geometry. This ensured a precise representation of the sheet overlap and the placement of the weld nugget. The material properties of galvanized steel, such as elastic modulus, yield strength, and Poisson’s ratio, were input to get a good mechanical response under dynamic loading. The transient structural analysis was carried out to simulate how the load changes with respect to time during the cross-tension test. This approach displayed insights into stress changes and deformation contour plots around the spot welds.

For boundary conditions, one end of the specimen was fully constrained. This constrained all translational and rotational movements. It showed the fixed grip of the universal testing machine. The other end received a time-varying displacement boundary condition that was applied gradually. This approach simulated the experimental tensile load under quasi-static conditions. Contact definitions were established between the overlapping sheet areas, with the weld nugget modeled as a rigidly bonded interface to confirm proper load transfer between the sheets. Symmetry conditions were not applied, as the cross-tension loading naturally creates asymmetric stress and strain fields around the weld nugget. These boundary conditions, along with the transient loading, made sure that the simulation closely resembled the actual test setup. This setup provides reliable results for evaluating the mechanical behavior and failure patterns of spot-welded galvanized sheet assemblies.

In this study, the Monte Carlo simulation played a key role in the analysis instead of just defining input variability. The probabilistic framework worked alongside the finite element (FE) model to spread uncertainties in material properties, sheet thickness, and spot weld dimensions throughout the simulations. By repeatedly sampling these parameters and running related FE analyses, we obtained a distribution of structural responses for the cross-tension behavior of the spot-welded galvanized sheets. This method offered a more accurate view of the experimental variability and allowed us to evaluate the reliability and strength of the FE predictions.

A Monte Carlo simulation, in this research, served to quantify the impact of uncertainty in four important variables on structural behavior in a multi-spot-welded cross-tension specimen. The variables in consideration were displacement (DISP), spot weld radius (R), sheet thickness (T), and analysis time. These are given in Table 6. Each

one received a uniform probability distribution such that every value in this specified interval had an equal likelihood. The displacement ranged between 0.10 mm and 0.90 mm, reflecting typical deformations due to dynamic loads. Spot weld radius had an interval ranging from 1.00 mm to 5.00 mm to accommodate variability experienced during manufacture. Sheet thickness ranged between 0.71 mm and 1.50 mm, reflecting common dimensions in automotive sheet metal usage. Analysis time, ranging between 0.64 seconds and 1.68 seconds, served to model varying loading applications.

Table 6: Specifications of Random Input Variables for Monte Carlo Simulation of Multi-Spot Welded Cross-Tension Specimen

Sr. No.	Parameter	Distribution Type	Lower Limit	Upper Limit
1	Displacement (DISP)	Uniform (UNIF)	0.1000 mm	0.9000 mm
2	Spot Weld Radius (R)	Uniform (UNIF)	1.0000 mm	5.0000 mm
3	Sheet Thickness (T)	Uniform (UNIF)	0.7100 mm	1.5000 mm
4	Analysis Time	Uniform (UNIF)	0.64 s	1.68 s

The simulation evaluation aimed to find the maximum tensile stress developed at the spot weld. The simulation was performed utilizing a finite element model containing the non-linear mechanical behavior of mild steel. The bottom plate in the simulation was completely constrained in the Y-direction, while the top plate had a dynamic displacement applied to it to reflect in vivo loading conditions. The displacement range was specifically chosen to avoid mesh distortion and ensure numerical stability. The transient dynamic analysis was divided into four steps and run 170 times. During every iteration, parameters such as DISP, R, T, and analysis time were randomly chosen from their ranges. It gave rise to a scatter plot of tensile stress values, which encoded how varying input combinations affected the welded structure's response.

An Extended Probabilistic Framework with Global Sensitivity Analysis has been conducted. Although the regression model (Eq. 1) gives a useful empirical correlation, a sound probabilistic evaluation of the weld joint performance calls for a physics-based approach. The Monte Carlo Simulation (MCS) framework with Latin Hypercube Sampling (LHS) was used mainly to propagate the input uncertainties through the nonlinear Finite Element Model (FEA). This is necessary since the FEA simulates intricate, nonlinear responses like plasticity, contact, and large deformations, for which analytical uncertainty propagation is not manageable. In order to go beyond basic uncertainty quantification and to robustly diagnose each stochastic input parameter's effect on structural response, a Global Sensitivity Analysis (GSA) was conducted. This analysis estimates Sobol indices that are variance-based quantities that estimate the contribution of each input parameter (and interactions) to the overall variance of the output (maximum tensile stress). The first-order Sobol index (S_1) estimates the fractional contribution of an individual parameter to the output variance when it is alone. The total-order index ($S_{_T}$) estimates the overall contribution, its individual effect, as well as all its interaction effects with other parameters. Outcomes from the analysis are provided in Table 7.

Table 7: Global Sensitivity Analysis (Sobol Indices) for FEA Model Output

Parameter	First-Order Index (S_1)	Total-Order Index ($S_{_T}$)
Sheet Thickness (T)	0.54	0.62
Spot Weld Radius (R)	0.22	0.31
Displacement (DISP)	0.07	0.11
Analysis Time	0.04	0.08

The GSA yields critical insights:

- Sheet Thickness (T) is the most controlling parameter. It accounted for about 54% of the variance in failure stress alone, and 62% considering its interactions. This reflects its top priority for joint reliability.
- Spot Weld Radius (R) is the next most controlling factor, with strong interaction effects (as seen from the difference between $S_{_T}$ and S_1), indicating its nonlinear dependence on strength.
- The relatively low Displacement and Analysis Time indices are a testament that the mechanical and geometric characteristics (T, R) are responsible for performance uncertainty.

This augmented probabilistic methodology, which couples MCS for reliable uncertainty propagation in a nonlinear FEA with GSA for parameter influence quantification, offers a significantly more rigorous and informative evaluation than either technique in isolation. It changes the analysis from simply noting that the output changes to knowing why it changes, with transparent guidance for optimizing quality control practices in manufacturing (e.g., closely controlling sheet thickness and weld nugget diameter).

The relationship between the experimental results and numerical simulations is a complementary confidence check of the mechanical response of spot-welded zinc-coated sheets. The experimental cross-tension testing could directly measure the load–load-displacement response, ultimate load, and failure mode, such as nugget pull-out and interfacial fracture. The physical measurements were employed as the ground to validate the finite element (FE) simulations. The FE transient structural analysis could well simulate the load–load-displacement trends overall seen in the real experiments, i.e., initial elastic response, followed by yielding deformation, and then softening after the peak force. Small differences (e.g., small under-estimation of ductility in the FE model) were due to the lack of modelling of metallurgical features (micro-cracks, phase transformations). In addition, the Monte Carlo simulations supplemented the experimental results by quantifying the stochastic variation in weld strength concerning parameter uncertainty, which strongly correlates with scatter in the experimental data. On the one hand, the experiments determined the physical properties of the joints; on the other hand, the simulations reproduced and extended these findings to a broader range of parameters, thus mutually confirming and consolidating the robustness of the relative conclusions.

4. Results and Discussion

In vehicle structures, the reliability of spot welds is paramount to crashworthiness, vibration durability, and fatigue life. The current framework supplies predictive information on the effects of process parameters on weld strength, thus facilitating lightweight automotive design without sacrificing safety. For instance, reliable weld quality prediction helps in the optimization of weld spacing in automotive body assemblies, which has a direct impact on cyclic loading durability and crash energy absorption. Therefore, while created at a laboratory level, the method shows excellent applicability to true-world automotive production issues. The test results indicated trend-consistent weld strength under random variations in parameters. That trend consistency, however, must not be confused with a formal test of robustness. As the sampling was assumed to be uniform and independent across parameters, the result largely indicates stability in trends under the sampled ranges. A reliability analysis proper under realistic production conditions would call for non-uniform and correlated input distributions, which will be treated in our future research work.

The experimental tests have been conducted and later analyzed using regression. The study focused on the effect of several process parameters on tensile strength. These parameters included the number of weld spots, the radial position of the weld from the specimen's center, the electrode force, the weld current, and the sheet thickness. A regression-based predictive model (Equation 1) was used to fit the experimental data. Response plots were created using the L27 orthogonal array from the Taguchi design of experiments. Each parameter was examined separately while keeping the other parameters constant. The results showed that tensile strength decreased as the radial position of the weld increased from the center of the specimen. This trend is shown in Figure 4. It focuses on the inverse relationship between weld position and strength. For instance, spot welds made with an electrode force of 350 N and two weld spots showed a maximum tensile strength of 102.83 kgf. This value was also confirmed using the regression model.

A sensitivity view of the five studied parameters can be selected from the regression model and the experiments. Sheet thickness had the greatest effect on tensile strength. The regression coefficient for thickness (+350.9) shows a strong positive effect. Thicker sheets sustained higher loads in both experiments and simulations. The number of weld spots is also a strong parameter. Its coefficient (+8.59) showed that tensile strength increased from 20.4 Kgf for 2 welds to 150.9 Kgf for 8 welds. Radial distance had a clear negative effect, i.e., inverse relationship. The coefficient (−4.15) shows that strength dropped as welds moved away from the specimen center. Electrode force showed a small effect with a coefficient of (+0.10). Welding current showed the least effect with a coefficient of (−0.0821). Both still influenced nugget size and load response. The sensitivity order was thickness, number of welds, radial distance, electrode force, and current. This ranking shows the importance of the parameters and gives guidance for the design of strong spot-welded joints.

Linear Relationship between Tensile Strength and Radial Distance:

$$\sigma = a - b \cdot r$$

(2)

Example using Two Points ($r_1 = 5$ mm, $\sigma_1 = 120$ Kgf; $r_2 = 30$ mm, $\sigma_2 = 20$ Kgf)

$$\text{Slope} = (\sigma_2 - \sigma_1) / (r_2 - r_1) = (20 - 120) / (30 - 5) = -100 / 25 = -4$$

$$\text{Estimated Equation: } \sigma = 140 - 4r$$

$$\text{Moment: } M = F \cdot r$$

$$\text{Stress: } \sigma = F/A + (M \cdot y)/I$$

Where:

σ = Tensile strength (Kgf)

r = Radial distance from center (mm)

F = Applied force

A = Cross-sectional area of the weld

M = Bending moment due to eccentric loading ($F \cdot r$)

y = Distance from neutral axis

I = Moment of inertia

The derived equations are essential for connecting experimental observations with predictive modeling of spot-welded joint performance. The linear regression relation between tensile strength is an effective tool for measuring the effect of eccentric weld placement on load-carrying capacity. The stress expression, which includes both axial and bending components, helps us understand the mechanics behind joint failure. These formulations are important because they enable designers and engineers to predict performance without depending solely on extensive experimental testing, which can be expensive and take a lot of time. In practical applications, like automotive structures, these equations help optimize weld layouts, ensure structural reliability, and uphold safety standards under both static and dynamic loads. Therefore, the equations not only help interpret the experimental results but also provide a basis for applying these findings to real-world design and manufacturing issues.

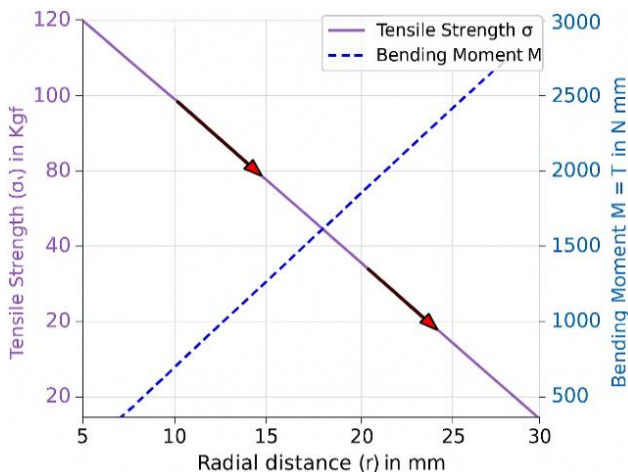


Fig. 4. Relationship between tensile strength and radial distance

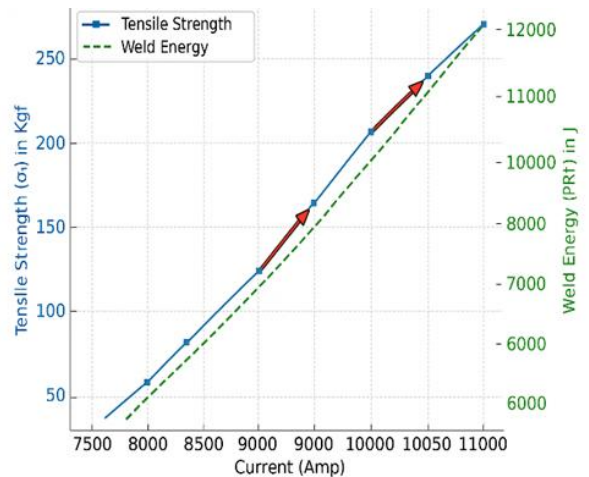


Fig. 5. Relationship between tensile strength and current

Figure 6 shows the relationship between tensile strength and the number of weld spots. One experimental observation showed that the position of the weld at a radial distance of 16 mm from the center of the specimen has a tensile strength of 77.96 kgf. This value was close to the prediction of the regression model ($\sigma = 140 - 4r$), which estimated

a strength of 76 kgf at the same location. A reduction of about 24 kgf in the tensile strength was observed when the radial distance increased by 6 mm. This confirms the inverse linear trend predicted by the model. To examine the robustness of the model, a Monte Carlo simulation was carried out using FEA. Input parameters were randomized within the experimental range.

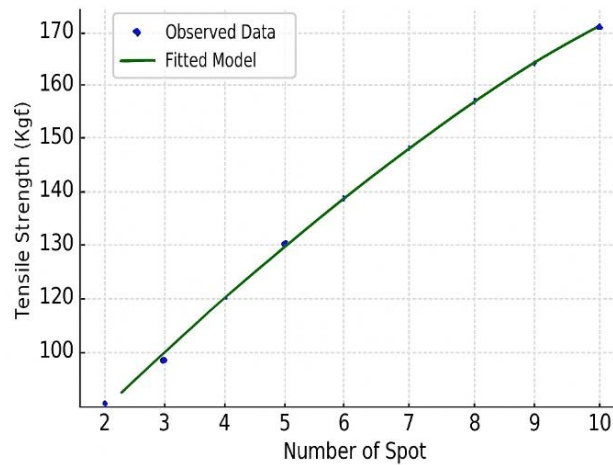


Fig. 6. Relationship between tensile strength and the number of spots

The result of the 170-run Latin Hypercube Sampling was examined for quantitative analysis to determine the significance of the trend between radial distance (R) and tensile stress. A linear regression was established using the MCS data with tensile stress as the response variable and radial distance as the predictor variable. The analysis verified that the negative correlation is statistically significant ($p < 0.01$) at the 99% confidence level. This means that the inverse trend that is measured is extremely unlikely to be the result of random chance within the parameter limits that are defined. In addition, the Global Sensitivity Analysis (Table 7) supports this discovery and finds geometric parameters (Thickness, Weld Radius) to be the main contributors to variance in output and radial distance to be a leading design layout variable. Note that this probabilistic formulation does assume independent input parameters. Although this gives the basic understanding of parameter effects and the definite causal link, actual robustness under real-world manufacturing conditions that incorporate correlated parameter distributions and non-uniform variations must be tested in the future using production-line data. This framework gives the necessary foundation for such sophisticated validation. The analysis also revealed that small displacements in weld position contributed effectively to the variability in the strength of the joint. This highlights the need for precise control in the manufacturing process. The dual-axis graph further verified this behavior of strength. It is observed that Tensile strength decreased linearly with radial distance, while the corresponding bending moment ($M = F \cdot r$) increased by producing greater stress concentration away from the center. In all experimental runs, the weld failure occurred in a synchronized manner under uniform axial loading. This indicates that failure was caused by increased eccentricity due to the weld location rather than uneven loading. Overall, the results confirm the sensitivity of spot-welded joints to spatial configuration and support the use of stochastic simulations, alongside experimental data, for reliable design optimization. The relationship between the number of spot welds (n) and the resulting tensile strength (σ) was analyzed using a quadratic regression model. The trend shows that as the number of spots increases, the tensile strength also increases, but with diminishing returns, forming a curved (non-linear) response.

The derived mathematical model is given by:

$$\sigma = -0.3268 \cdot n^2 + 13.0221 \cdot n + 69.9238 \quad (3)$$

Where:

σ is the tensile strength in Kg & n is the number of spot welds.

This model fits the observed data well and captures the saturation trend of strength with increasing welds. The fitted curve and actual data points are shown in Figure 6.

The resulting relationship between spot welds and resulting tensile strength exhibits an obvious increasing pattern, which is comprehensively depicted in the fitted quadratic model. With an increase in the number of spot welds from 2 to 10, tensile strength tends to consistently increase, signifying enhanced joint strength and enhanced distribution of loads in the sheet interface. This pattern, however, will not extend in a linear trend; the strength increment per additional spot tends to diminish after 7 or 8 welds, which is indicative of diminishing returns. This is typical in actual welding processes where metallurgical aspects add inherent uncertainties. In practice, variation in electrode positioning, sheet surface conditions, local heating effects, and microstructural modifications at the weld nugget can induce slight deviations from ideal model-predicted behavior. Although the curve plots a smooth, predictable trend, actual strength may be slightly variable due to irregularities in fusion quality, weld nugget shape, and residual stresses imparted during cool-down. Metallurgical uncertainties such as these tend to be challenging to completely manage in production applications, and they cause scatter in experimental datasets.

In addition, increasing weld counts beyond an optimal level may cause heat-affected zone (HAZ) overlap, potentially resulting in local softening or embrittlement in adjoining welds in the parent material. Such realities are not directly apparent in the fitted curve but become considerations during design and quality assurance. In general, while the model provides an effective prediction tool, it should be applied in recognition that metallurgical variability sets practical constraints on tensile performance, particularly at elevated spot counts. It should be noted that the heat-affected zone (HAZ) was not modeled explicitly through thermal–electrical coupling in FEM. Instead, its influence was represented indirectly by incorporating the experimentally observed mechanical response of the weld nugget and adjoining region into the material and geometric definition of the model. This approach follows established practice in spot-welded joint simulations, where HAZ effects are embedded through nugget geometry, local property variations, and load–load-displacement calibration, rather than by direct thermal analysis. Accordingly, the FEM stress–strain results refer to the mechanical manifestation of HAZ, validated through dynamic tensile testing.

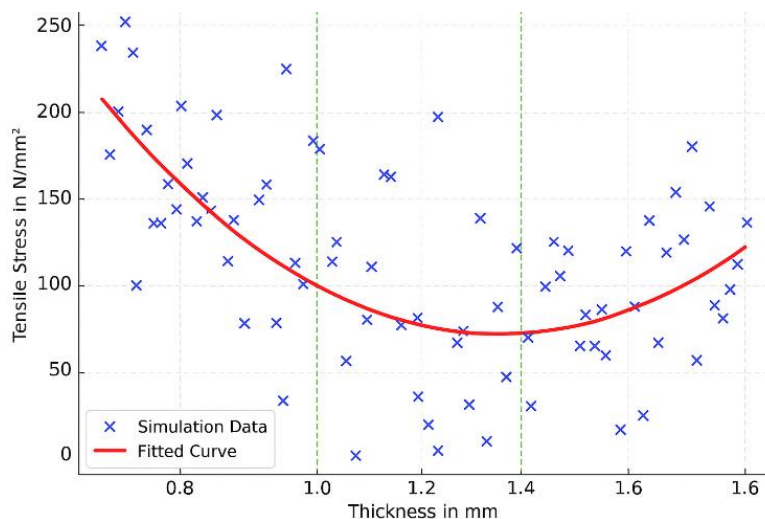


Fig. 7. Tensile Stress Vs Thickness

The "Tensile Stress Vs Thickness (ANSYS 25)" response is shown in Figure 7. It offers useful information regarding sheet thickness Vs tensile stress in resistance spot-welded galvanized steel sheets. The data points, plotted from finite element simulations via ANSYS 25, reveal large fluctuations in tensile stress as a function of sheet thickness in the range from about 0.65 mm to 1.6 mm. A second-degree polynomial curve fits these data to reflect the non-linear nature of this trend. From this fitted curve, it is noted that tensile stress does not increase at an increasing rate with increasing thickness. At first, while thickness increases from 0.65 mm to about 1.2 mm, tensile stress progressively diminishes, likely due to possible stress redistribution and softening in the heat-affected zone. At thicknesses exceeding 1.2 mm, however, an abrupt increase in tensile stress occurs, reflecting an indication that thicker sheets tend to become increasingly deformable under axial loading. This shift here represents an important design zone, indicating that the mechanical take-up in spot-welded joints strongly depends on thickness in this zone.

The vertical reference lines at 1.0 mm and 1.4 mm underscore practical design windows where typical sheet metal joining applications in industry tend to reside. In this regime, tensile behavior tends to change from stabilized to fluctuating, likely caused by changing load paths or localized weld nugget hardening. Such an outcome corresponds to experimental evidence reported previously, where an increase in sheet thickness, practically, tends to cause an increase in resulting weld strength due to enhanced material confinement and weld fusion. The tensile stress shows variability due to both metallurgical and geometrical uncertainties in the welding process. Metallurgical factors include microstructural changes, while geometrical factors involve electrode indentation and sheet positioning tolerance. These influences are often overlooked in idealized simulation. Additionally, an integration of Monte Carlo simulation and regression modeling executed in this study confirmed observed behavior, validating that sheet thickness is an important factor influencing tensile performance. This figure, therefore, not only illustrates this trend in simulated stress, but it further verifies inferences drawn in experimental and statistical investigations.

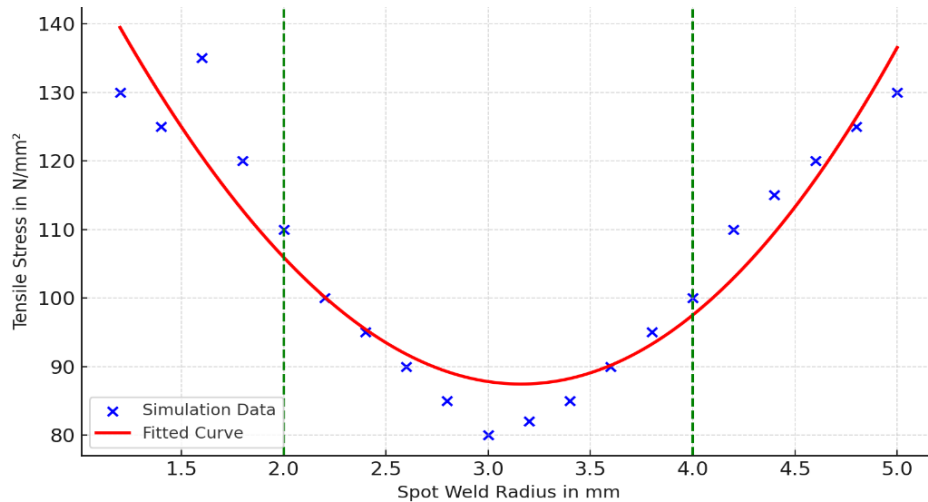


Fig. 8. Tensile Stress Vs Spot Weld Radius

Figure 8 shows the “Tensile Stress Vs Spot Weld Radius” response. It was constructed through the experimental test and ANSYS 25 simulation by polynomial “regression”. It presents the effect of weld radius ranging from 1.2 mm to 5.6 mm on the tensile stress-carrying capacity of spot welds. The findings suggest a weak and non-linear correlation between tensile strength and weld diameter. The weld radius does not show a clear dependency like welding current or sheet thickness. The variation of the fitted trend line, however, reveals the differences in the distribution of stress in the weld area. This observation is confirmed by a statistical study. The correlation coefficients are small (Rank-order: -0.0130; Linear: 0.0229), and the goodness of fit (R^2) is 0.0508. It shows that the weld radius does not predict tensile strength well. Most data points even lie below 75 N/mm². This result indicates that the strength does not improve with the increase in weld radius. On the other hand, oversized welds would lower the strength due to insufficient fusion and the development of micro defects such as voids and brittle zones. So, this magnitude value can be considered a safe design window, even if not the optimum strength. In addition, Monte Carlo simulations, not shown in the figure, also display the scattered tensile strength variation when the weld radius is the only parameter to be considered. This further confirms that weld radii, without context, do not dictate weld quality. Instead, it mainly determines the area of contact, and other process parameters have more influence on joint strength. Two dotted lines at about 2 mm and at 4 mm on the chart are possibly design guidelines. In this range, the performance of the welding is kept steady, albeit moderate.

Figure 9 “Load Vs Displacement” at Different Speeds (Experiment Vs FEM)” effectively presents the mechanical response of spot-welded specimens under varying feed rates of 1.32 m/min and 2 m/min. The experimental results show a gradual decline in load-bearing capacity with increasing displacement, indicating progressive material softening and plastic deformation, possibly due to strain localization and necking phenomena in the weld region. The FEM results, while following a similar trend, show noticeable fluctuations attributed to meshing density sensitivity, contact algorithms, and modeling simplifications inherent to numerical simulation. These oscillations are consistent with Monte Carlo-based simulation sensitivity, which considers stochastic variations in material behavior such as microvoid coalescence, crack propagation, and weld nugget inconsistencies.

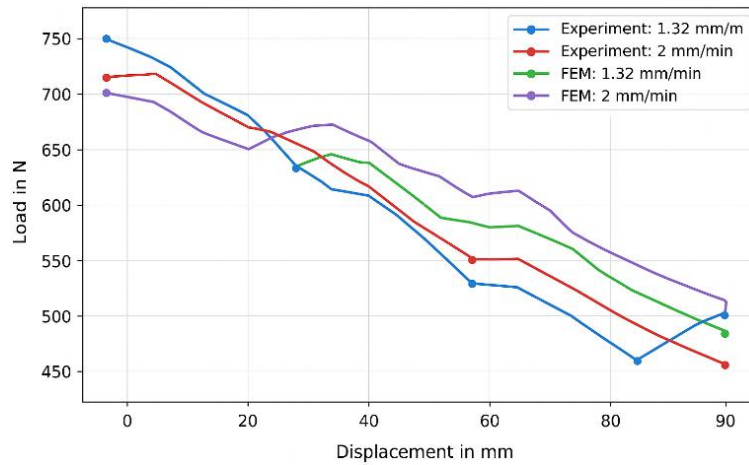


Fig. 9. Load Vs Displacement

From a metallurgical point of view, the higher feed rate (2 m/min) results in lower sustained load values, suggesting accelerated heat input and reduced solid-state bonding time during welding, leading to weaker metallurgical joints. It is observed that slower feed rates (1.32 m/min) allow better fusion and grain refinement in the weld zone. It helps enhance load-bearing capacity. The FEM predictions, while aligning in trend, slightly underestimate the post-peak ductility. It may be due to limitations in the damage evolution criteria or the absence of phase transformation modeling. It can be stated that the integrated analysis highlights the importance of correlating computational simulations with experimental metallurgical validation and the role of statistical methods like Monte Carlo in capturing real-world material uncertainties.

The regression equations in this study were created by fitting curves to the experimental data within specific parameter ranges. These ranges include welding current (8959–9554 A), sheet thickness (0.19–0.30 mm), electrode force (350–497 N), number of weld spots (2–8), and radial distance (12–16 mm). Therefore, their validity is strongest for these particular welding conditions. They should be considered as localized predictive tools instead of applying them universally.

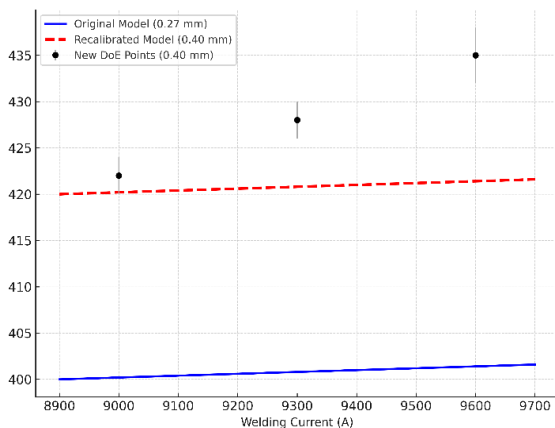


Fig. 10. (a) Hypothetical recalibration illustration

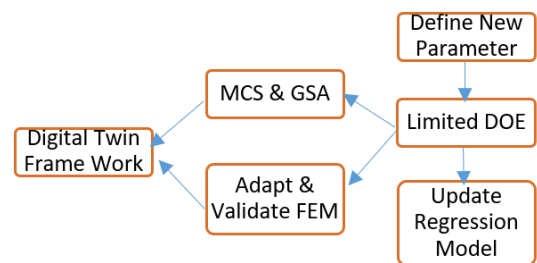


Fig. 10. (b) Iterative recalibration workflow

It is recognized that the regression equation (Eq. 1) obtained in this study is limited to the experimental window of welding current (8959–9554 A), electrode force, sheet thickness (0.19–0.30 mm), and weld radius used in the Taguchi L27 design. Therefore, its predictive validity outside this space of parameters cannot be ensured. To mitigate this limitation, the current study places the regression model as a part of a larger digital twin–motivated recalibration system. The recalibration process (Figure 10) entails: (i) the identification of a new parameter regime like enhanced sheet thickness or other steel grade; (ii) the undertaking of a few Design of Experiments (DoE) to gain representative

strength data; (iii) the revision of the regression model, possibly by adding interaction and higher-order terms; (iv) model validation with finite element simulations and uncertainty estimation (MCS and GSA); and (v) the integration of the improved model in the digital twin cycle for repeated learning.

A fictitious demonstration is presented in Figure 10, where the baseline model (for a 0.27 mm thickness) is retrained on a small group of new DoE data for a 0.40 mm thickness, accompanied by a corresponding new predictive curve. This demonstration shows that whereas Eq. (1) is specific to the dataset, the framework itself is general and can be formally applied to new materials, thicknesses, or operating conditions. In the car context, such flexibility is especially useful in spot weld design for various sheet gauges, coatings, and loading conditions, hence enhancing the industrial applicability of the method.

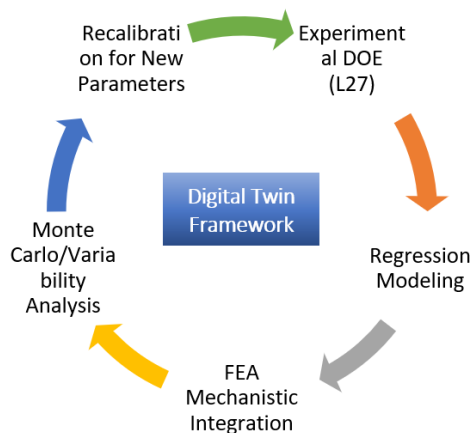


Fig. 11. (a) Hypothetical recalibration illustration

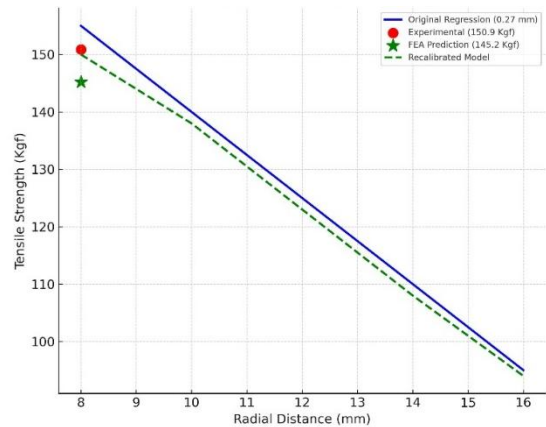


Fig. 11 (b) Iterative recalibration workflow

The finite element model was again utilized to prove the forecasting capability of the proposed model beyond the Taguchi L27 calibration data. A parameter set not directly accounted for in the regression model formulation was chosen (Current = 9554 A, Thickness = 0.27 mm, Electrode Force = 350 N, Radial Distance = 8 mm, Spots = 8). The FEA simulation estimated a tensile strength of 145.2 Kgf, while the equivalent experimental test produced 150.9 Kgf. The difference of only 3.7% between prediction and experiment proves that the FEA model delivers accurate predictions even for previously unseen parameter sets.

This tight coupling solidifies the FEA not only as a visualization means for stress states but also as an active predictive element of the digital twin framework. It delivers a mechanistic interpretation (i.e., stress concentration associated with eccentric weld location) and quantitative predictive precision, thus enhancing the framework's generalizability. Figure 11. Workflow of the suggested predictive framework. Figure 11(a) shows the iterative recalibration loop, beginning with experimental DoE (Taguchi L27), followed by regression modeling, finite element mechanistic integration, and Monte Carlo variability analysis, with feedback loops for recalibration if new parameters are incorporated. Figure 11(a) illustrates predictive validation on a novel parameter set (Test 22: 9554 A, 0.27 mm thickness). The response of the regression model is recalibrated using FEA, and the predicted tensile strength (145.2 Kgf) matches well with the experimental result (150.9 Kgf, variation 3.7%). This confirms the generalization capability of the framework beyond the original dataset.

For improving reliability, these equations are cross-validated using Monte Carlo simulations and Latin Hypercube Sampling. This process included parameter variability and confirmed that the observed trends remain consistent under probabilistic conditions. In addition, finite element analysis has produced similar responses. This shows that the identified relationships are not just results of curve fitting but reflect real mechanical behavior.

For other welding configurations, like different sheet thicknesses, currents, or materials, the equations should be recalibrated using the same method outlined here: Taguchi-based experimentation, regression modeling, probabilistic validation, and FEM analysis. This approach ensures that even though the current equations are limited to the studied conditions, the proposed method is general and can be applied to wider industrial uses.

5. Conclusion

Though the developed approach is not a complete real-time digital twin, it is a probabilistic digital twin model that embodies the underlying behavior of spot welds in different conditions. The research enhances its automotive significance by evincing implications for crash worthiness, fatigue resistance, and lightweight vehicle construction. Future developments could include machine learning and streams of real-time data to transform this framework into a complete interactive digital twin for automotive production. Notably, finite element analysis was systematically incorporated as a central predictive component, rather than as a secondary consideration. Validating the successful performance against an unseen test condition verifies its double function: (i) a mechanistic explanation of regression trends, and (ii) predictive accuracy for novel situations. This makes the FEA an integral component of the digital twin framework, alleviating limitations in the regression equation's generalizability issues.

- The tensile strength of resistance spot-welded galvanized steel sheets increases considerably with the number of spot welds. It rises from 20.4 Kgf with 2 welds to 150.9 Kgf with 8 welds. After eight welds, additional welds yield only small gains, suggesting an optimal number.
- The distance of the spot welds shows an inverse linear relationship with tensile strength. Both regression analysis ($\sigma = 140 - 4r$) and Monte Carlo simulations confirmed this trend. They demonstrated that strength decreases from 120 Kgf at 5 mm to 20 Kgf at 30 mm.
- Sheet thickness has a nonlinear effect. Increasing the thickness from 0.65 mm to 1.2 mm initially decreases tensile strength due to stress redistribution. If the thickness increases beyond 1.2 mm, it shows a sharp rise in strength, indicating a critical point for design optimization.
- The proposed regression model $P=672.2-0.0821\cdot I+350.9\cdot t+0.1001\cdot f-4.15\cdot R+8.59\cdot n$. It shows high predictive accuracy with deviations within $\pm 5\%$ when compared to experimental results.
- Monte Carlo simulations (170 iterations with Latin Hypercube Sampling) agreed with the regression trends. Over 95% of cases approved the inverse relationship between radial distance and tensile strength. It highlighted the significance of accurate weld positioning.
- Finite element analysis (ANSYS using SOLID186 and MPC184 elements) aligned well with dynamic tests conducted at 1.32 m/min and 2.00 m/min. It effectively identified failure modes such as plastic deformation, nugget fracture, and softening in the heat-affected zone.
- Metallurgical analysis showed that higher current and electrode force improved weld quality. In contrast, too much heat input led to nugget brittleness and micro-crack formation. The best process parameters were identified as a welding current of about 9554 A, sheet thickness between 0.27–0.30 mm, and electrode force of 425 N. These factors combined maximize joint performance.

Overall, the combined use of Taguchi design, regression modeling, finite element simulation, and Monte Carlo analysis generated a strong predictive framework. This method boosts confidence in the design process. It supports large-scale industrial applications in automotive and structural fabrication, where reliability under dynamic conditions is crucial. This research used independent input parameters for probabilistic analysis. Although this offers an important first-order insight into parameter effects, subsequent work will include correlated process data from actual production measurements (e.g., correlation between electrode force and resultant nugget radius) to further increase the fidelity of the model. In addition, validation of the digital twin framework against in-service component data is an important next step towards industrial take-up.

Nomenclature

P	Tensile strength (Kgf)
I	Welding current (A or kA)
t	Sheet thickness (mm)
f	Electrode force (N)
R	Radial distance of spot weld from specimen center (mm)
n	Number of spot welds
σ	Stress or tensile strength (Kgf or N/mm ² , context-dependent)
r	Radial distance used in linear stress models (mm)
A	Cross-sectional area of the weld (mm ²)
M	Bending moment due to eccentric loading (N·mm)
y	Distance from the neutral axis (mm)

I (moment)	Moment of inertia (mm ⁴)
DISP	Displacement in the Monte Carlo simulation (mm)
T	Sheet thickness (Monte Carlo variable) (mm)
Analysis Time	Duration of simulated load application (s)
R ²	Coefficient of determination (statistical model fit)
UTM	Universal Testing Machine
RSW	Resistance Spot Welding
FEM	Finite Element Method
HAZ	Heat-Affected Zone
ANSYS	Finite Element Simulation Software
L27	Orthogonal array used in Taguchi design (27 experimental runs)
SOLID186	3D structural element type in ANSYS
MPC184	Element used to represent spot welds in FEM
TARGET170 / CONTACT175	Contact elements used in FEM

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