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DEVELOPMENT OF A PREDICTION MODEL FOR THE BEHAVIOR OF BOLTED STRUCTURE WITH AN ELASTIC PART JOINT BASED ON METAMODEL APPROACH

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This paper aims to establish a metamodel for predicting the mechanical behavior of bolted structures with elastic parts, regardless the changes in input parameters from a set of simulation data. First, we collect information from a parametric analysis based on numerical finite element simulation tests. Then, the metamodel is built using the radial spline basis function method. Following that, an iterative fitting process based on the metamodel-simulation coupling is used to improve the model's fidelity. Finally, the metamodel is validated by comparing and analysing the error rate between the metamodel and the simulation in order to reduce the computation time towards 2 seconds.

Keywords: bolted mechanical structure, metamodel, dynamic analysis, radial basis function method (RBF), stress von mises and strain

1 INTRODUCTION

Numerical simulation modelling is one of the most useful and widely used techniques for analyzing and evaluating the dyna- mic behavior of complex mechanical manufacturing systems. In the literature, the development of these numerical techniques, as well as computational and design techniques based primarily on numerical simulations, like the finite element method (FEM), remains one of the most fruitful lines of research to understand and explain this dynamic behavior. In this type of analysis, the variability of the different input parameters describing the structure studied must be taken into accounts, such as geometric parameters, material properties, and applied loads. On the other hand, numerical simulation remains an effective tool for overcoming the complexity of random input variables and producing probabilistic results. As a result, conceptual models known as metamodels are critical for replacing simulation models and significantly lowering their costs [1].

In the literature, bolted structures are considered a practical application for predicting their mechanical behavior. They are increasingly used in most critical industries, such as aviation and automotive. These fields require a high level of performance, and these structures provide good stiffness and security for their mechanical components' assembly. Several studies [2–4] have been conducted to simulate this type of structure. In this case, installing an elastic piece between the two plates in the joint area can improve the structure's performance. The first purpose of this technique is to absorb the stress distribution caused by a large vibration transfer and Von Mises stress from one plate to another. The second purpose is to reduce structural element deformation caused by the same transfer described previously [2]. The addition of an elastic part between two bolted plates significantly increases the non-linearity of the structure's behavior, Changing the structural parameters causes different behavior, which makes it very difficult to predict.

Efficient stochastic or evolutionary optimization of non-linear structures requires testing a large number of optimization parameters, and numerical finite element simulations of complex structures are known to be time-consuming, which makes the operation very expensive. The use of metamodels can greatly facilitate optimization improvements by allowing efficient optimization with very short computations and using very large numbers of data and iterations.

In the literature, to better match the finite element model results to the measured data of the bolted structure, Yunus et al. [5] used meta-modelling techniques to modify and correct the finite element model to obtain dynamic responses similar to real experience while reducing simulation costs. This fast agreement with measured data can be used for the analysis of similar structures.

Similarly, Mathern et al. [6] exploited kriging metamodeling to carry out a multi-objective design optimization for a reinforced concrete foundation for wind turbines while including durability and constructability objectives. In comparison to designs created using more conventional techniques, the findings of kriging enable for the creation of an optimal design for many combinations of objectives while shortening the simulation time. The obtained results support the findings of [4] and [5], demonstrating that the proposed metamodel can reliably replace the finite element simulation model while reducing computation time.

The coupling of the experimentally validated finite element models and the metamodel enables the solution of a multi-objective optimization problem to generate new solutions that improve the performance of the energy absorption by improving the geometry of the multi-cellular aluminum extruded crash rail. Booth et al. [7] employed a metamodel process to achieve this goal, with Response Surface Methodology (RSM) being used to perform the multi-objective optimization analysis. The traditional RSM approach is compared to an adaptive surrogate assisted response surface method (ASA-RSM) in terms of speed and ability to correctly identify the true Pareto front. This comparison demonstrated that the ASA-RSM approach could identify a significant percentage of the true Pareto front while only using 42% of the domain. This study provides a comprehensive understanding of the performance gain of multi-objective optimization when applying the structural shock resistance under different loading conditions.

The metamodel is used in several research areas to analyze and optimize aerodynamic shape design problems in conjunction with optimization algorithms. The use of metamodels in optimization problems, either separately or during the optimization loop, allows for a reduction in overall computational costs [7]. Reliability-based optimization with the metamodel remains an efficient method for computing the quantile by estimating the real constraint on a subset of MCS samples rather than all MCS samples [10]. This also avoids the problems associated with Monte Carlo simulation in RBTO (MCS). Truss, beam, and bridge tests in [8] validate the evaluation of efficiency, effectiveness, and accuracy.

According to these previous results, the metamodel is now regarded as one of the best approaches and methods for evaluating the deterministic or stochastic outputs of any analysis model in a fast and reliable manner based on variations in the inputs. These results also demonstrate the conditions for successful coupling of metamodel approaches and FE simulations [9] for multi-objective optimization of the investigated structures.

The main objective of this paper is the development of a powerful tool for generating models from changes in structural parameters that can predict the behavior of the bolted structure discussed in [2] under the influence of external mechanical actions without the use of numerical simulations. This analysis entails evaluating output data such as Von Mises stress and strain. The following is how the rest of the paper is structured. In Section 1, we begin with a description of the bolted structure under consideration. Next, we employ the finite element (FE) simulation method to investigate the parameters that can affect the stress concentration and strain in a bolted joint as a function of different elastic part thicknesses and materials, as well as different mechanical action values. ABAQUS software is used for numerical finite element simulation. Following that, the ABAQUS simulation process is explained, accompanied by the simulation results (simulation inputs and obtained data). Then, we use the simulation results to create a metamodel capable of evaluating output data independent of input values. In this context, we present the metamodel construction process, as well as an explanation of the techniques used and a numerical application on MATLAB. These applications allow for the evaluation of the constructed metamodel's performance by comparing its results to the numerical simulation results obtained by ABAQUS.

The section that follows aims to apply a check and adjustment process to compare the results of the metamodel and the finite element simulations to ensure the fidelity of the constructed metamodel. This control and adjustment process allows us to reconcile the metamodel's output values with those of the numerical simulations. This method yields reliable results that can be used to analyze the dynamic behavior of bolted structures at a low cost. We conclude with a conclusion and some future perspectives.

2 PARAMETRIC ANALYSIS OF THE BOLTED STRUCTURE

2.1 Description of the studied structure

Bolted structures are subjected to simple and compound mechanical actions in practice. To perform the numerical simulation in our study, we use the model FE of [2] (see Figure 1). compression stress is applied to the bolted structure under investigation, and a piece of elastic material is placed between the two steel plates in the joint area. Figure 1 depicts all the parameters that were used. The thickness, width, and length of the elastic piece and the two plates, as well as the diameter of the hole from the middle to the contact area, are structure design parameters. To carry out the numerical simulations, the thickness of the elastic piece e was varied from 0.2 m to 2 mm.

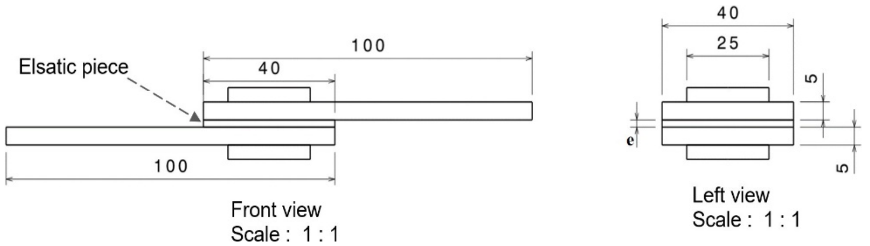


Fig. 1. The overall drawing of the studied structure with Joint

2.2 Compression test simulation

To simplify the finite element (FE) model mesh, we first subdivide the geometry of the studied structure into elements with equivalent behavior. The simulations are carried out using the ABAQUS software. It also allows you to simulate the behavior of parts or structures made up of polymer or four elastomer elements, taking non-linearities, large deformations, and temperature effects into account. Thus, static or dynamic analyses can be performed, for example, for sealing issues, vibration analyses, etc. Figure 2 depicts the definition of the investigated structure.

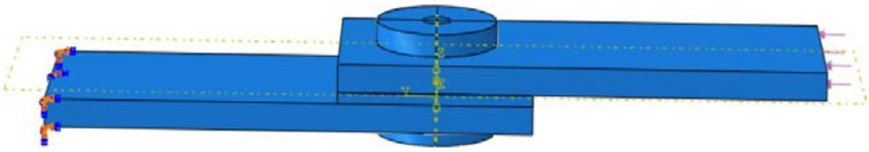


Fig. 2. A bolted structure compression test numerical experiment

The material properties of the different parts of the structure were chosen according to the type of material. For all the simulations, the two plates and the bolt are made of steel and the material of the joint is chosen among the 4 types of materials listed in table 1. All the information related to the material properties of all the parts is also presented in table 1:

Table 1. Material properties of the structure components

		Young's Modulus E(MPa)	Poisson ratio	Density (T/mm^2)
Steel plate & Bolt		210e3	0.3	7.8e-9
Elastic part	Butyl Rubber	6	0.49	1.5e−9
	Polyurethane	11.3	0.47	1.2e−9
	Ethylene Acetate	30	0.49	1.59e−9
	Silicone Elastomer	50	0.49	1.22e−9

Compression loads ranging from 50N/mm^2 to 200N/mm^2 were applied to the upper face of the top plate in the simulations presented in this paper (see, Figure 2). To investigate the structure's dynamic response, the elastic piece's thickness ranged from 0.2mm to 2mm, and its material was chosen from the four materials listed in Table 1. First, we chose the elastic piece's initial parameters, setting its thickness to and e = 0.2mm and selecting its material from the four options listed in in the table above. Second, we used the various pressure force values that we had chosen. We used the same mechanical actions every time we changed the material. Finally, after changing the material and mechanical action values, we changed the thickness of the elastic piece and repeated the previous operations under the same conditions.

The dynamic response will be examined in terms of the distribution of Von-mises stresses and strain as a function of the applied mechanical actions, thickness and material of the elastic part. This distribution is taken at an element of the lower plate in the assembly area. The selected element must be located in the contact area where the Von-Mises stress and strain distribution is the most important.

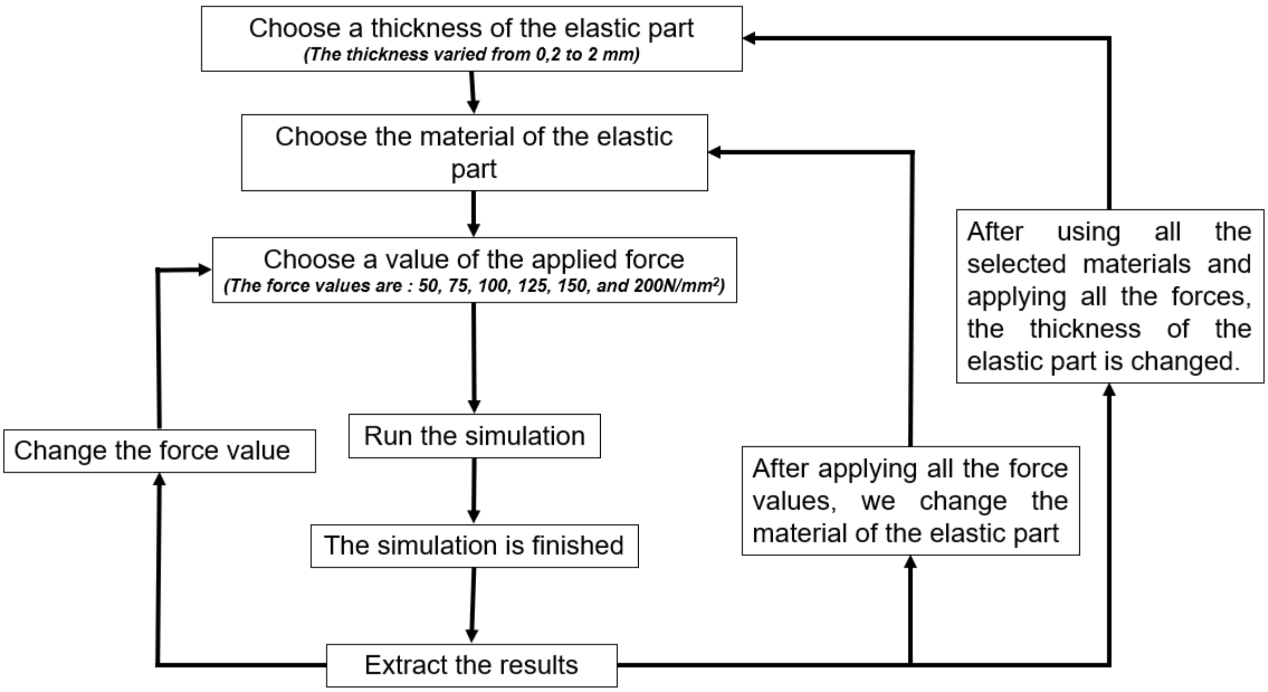


Fig. 3. Numerical calculation flowchart

All the simulations below use an explicit dynamic step. The contact properties between the structure's parts are defined by a coefficient of friction for each contact, and friction also achieves lateral contact between the bolt and the plates. The friction coefficients used for this numerical calculation are shown in the table below:

Table 2. Friction coefficient for each contact

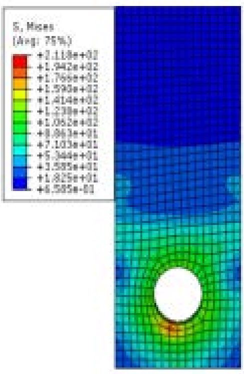
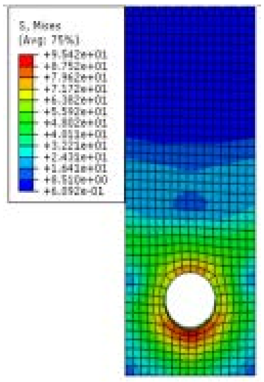
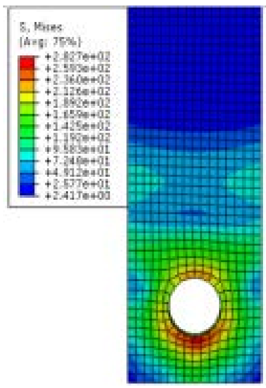
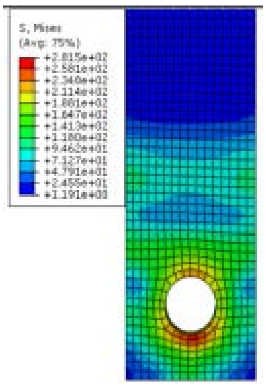
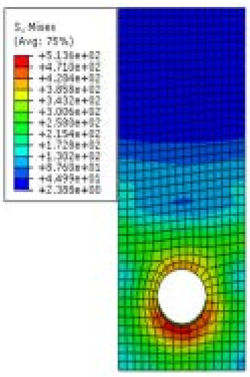
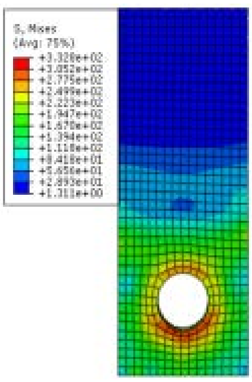
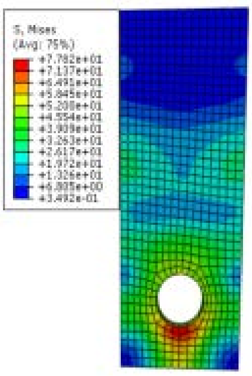
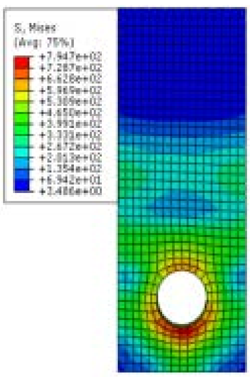
Type of contact	Friction coefficient
Steel/Steel	0.26
Steel/Butyl Rubber	0.45
Steel/Polyurethane	0.5
Steel/Ethylene Acetate	0.2
Steel/Silicone Elastomer	0.2

The plates' mesh is created by hand using the Mesh library. The steel plates are divided into 2.5 mm square elements, and the shape of these elements varies slightly as they approach the hole. The mesh of the joint is then created manually based on the thickness. The bolt mesh is then generated automatically. Following that, all input data (elastic part thickness, elastic part material, and mechanical actions performed on the top plate) are entered. Finally, the simulation can be run, and the results extracted.

2.3 Results Finite Element simulation

Finite element analysis (FEA) is used in place of actual experimentation. It allows for quicker and less expensive results when explaining physical experiments. To calibrate a FE model and achieve results that are comparable to the real experiment, reliable test data are required. If the FE analysis is validated, the structure's dynamic response can be modelled using a variety of input parameters. The following elastic part thicknesses were selected: 0.2mm, 0.4mm, 0.6mm, 0.8mm, 1mm, 1.2mm, 1.4mm, 1.6mm, 1.8mm and 2mm. One of the four elastic part materials listed in the table 1 is selected for each thickness, and mechanical actions of 50N/mm^2, 75N/mm^2, 100N/mm^2, 125N/mm^2, 150N/mm^2, 175N/mm^2 and 200N/mm^2 are applied one after another. The output data is extracted after each application of a mechanical action. We move on to the other materials and repeat the process used on the structure studied with the first material once we have finished applying all the mechanical actions on the structure using the first material. The simulation results in terms of stress and strain distribution in the lower plate with a thickness of 2mm for the joint are presented in the following two tables.

Table 3. Stress distribution on the lower plate for a 2 mm part thickness

Force Value (N/mm^2)	Elastic part material			
	Butyl Rubber	Polyurethane	Ethylene Acetate	Silicone Elastomer
50				
125				

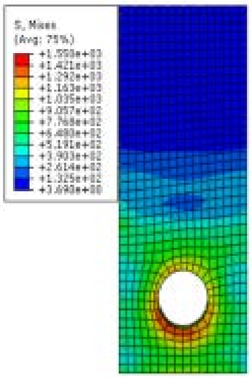
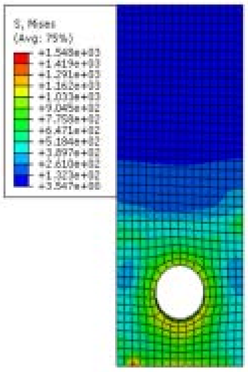
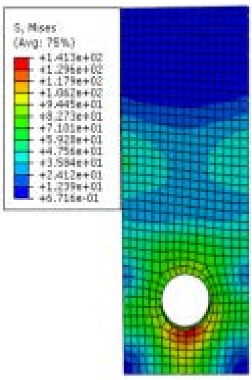
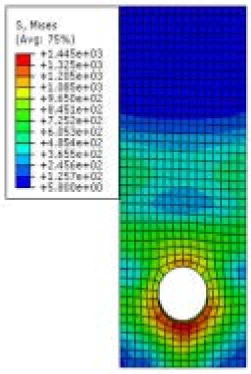
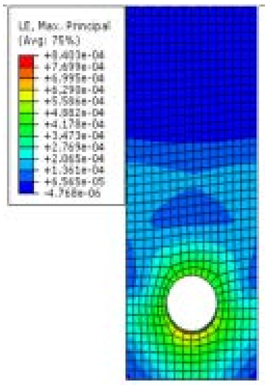
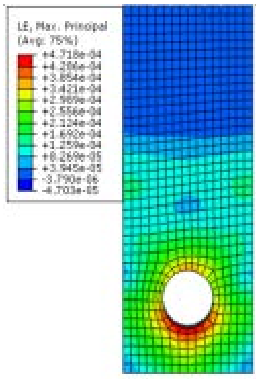
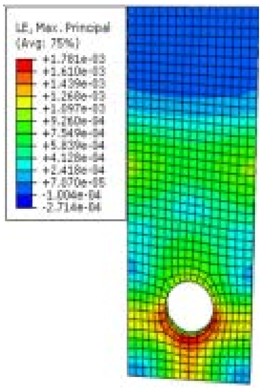
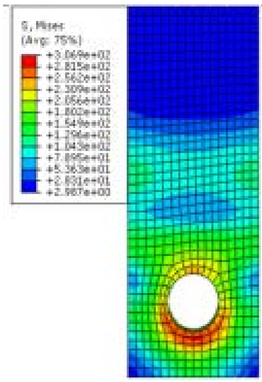
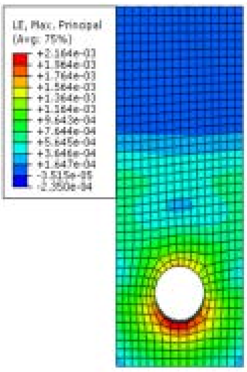
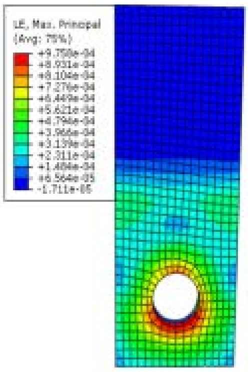
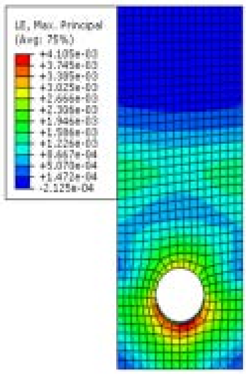
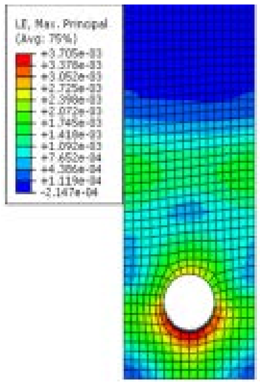
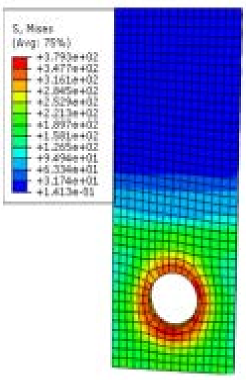
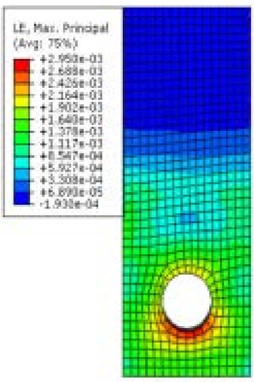
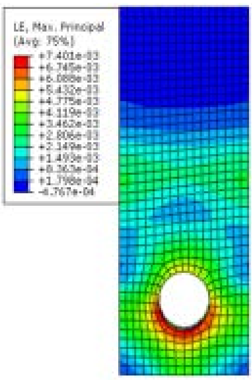
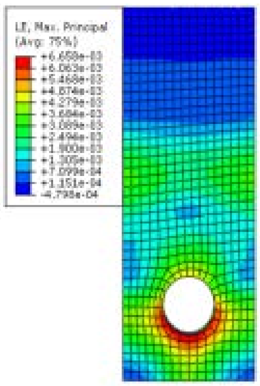
Force Value (N/mm^2)	Elastic part material			
	Butyl Rubber	Polyurethane	Ethylene Acetate	Silicone Elastomer
200				

Table 4. Strain distribution on the lower plate for a 2 mm part thickness

Force Value (N/mm^2)	Elastic part material			
	Butyl Rubber	Polyurethane	Ethylene Acetate	Silicone Elastomer
50				
125				
200				

The simulation results shown in tables 3 and 4 show that the von-mises stress and strain distribution on the lower plate is concentrated near the hole. These Results also show that the stress and strain values increase when the mechanical actions are increased, regardless of the nature of the elastic piece material. Thus, the variation of the elastic part's geometric and material parameters has a significant effect on the Von Mises stress and strain distribution. Furthermore, simulations on different thickness values show that an increase in young's modulus (material change) results in more concentrated stresses and strains in the assembly area.

3 METAMODEL BUILDING

The use of various computer tools in the engineering environment is required to design products and mechanical structures and to facilitate the analysis of their behavior. In practice, there is CAD software for design and CAE software to analyze the behavior of CAD-designed structures. Although some software packages include integrated CAD and CAE libraries. Structure optimization options in CAD systems are limited [11]. Furthermore, neither environment's software was fully utilized for structural optimization. Because this software is frequently used for a single simulation that takes into account previously determined input data to evaluate the output data. While dynamic behavior analysis and structural optimization always necessitate a cycle of analysis and evaluation. This loop allows for automatic and reliable output evaluation while changing the input data. The use of the metamodel remains a very powerful tool for creating this loop that facilitates the evaluation of the outputs based on the input data. To develop the latter, a set of data from the CAD-CAE simulation by finished elements must be prepared.

There are several techniques and methods for developing metamodeling in the literature. Kriging [10], inductive learning [13], neural networks [12], response surface (RSM) [14], and radial basis functions method (RBF) [15] are examples of techniques that can be used alone or in combination. In this paper, the latter method is used to create a metamodel that analyses the dynamic behavior of bolted structure. The metamodel proposed in this article is being developed in three steps:

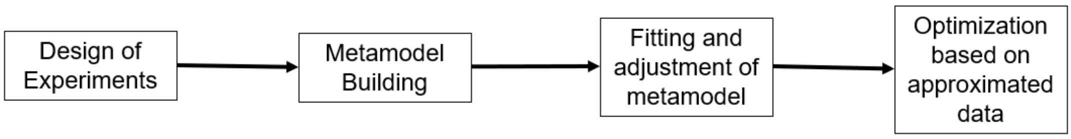


Fig. 4. The proposed metamodel's process

The first step in the metamodel construction process is to choose design of experiments (DOE) that can handle the obtained experimental data. The design of experiments chosen belongs to the family of full factorial designs, which aim to fill the design space while ensuring good homogeneity and coverage of the design space. It can also better represent the target function that we want to approximate using the metamodel. Following the selection of the design of experiments and the definition of the set of co-factors, the next step is to construct a metamodel that describes the relationship between the inputs and outputs. Then, to minimize the error between the results of the experiment and those of the metamodel, an adjustment process is applied by introducing new values belonging to the design of experiments, in the metamodel and in the simulation. The metamodeling interpolation techniques are applied to approximate the outputs for untested experimental design data or for data that does not belong to the design of experiments. The process of creating the metamodel is illustrated in Figure 5, starting with the structural analysis of the bolted structure and progressing to interpolation using the metamodel.

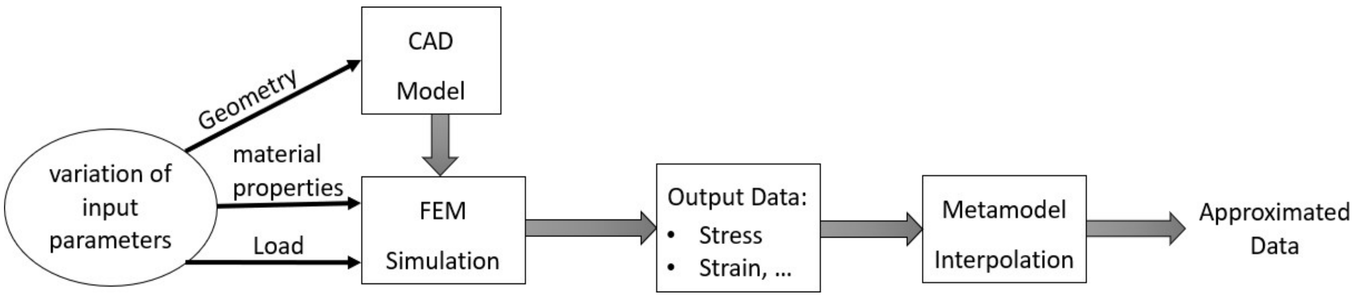


Fig. 5. Metamodel building process

3.1 Interpolation metamodel technique

In the context of developing the metamodel that approaches the behavior of the bolted structure with the elastic part, the Radial basis function method (RBF) remains an appropriate tool. FBR is a neural network meta-modeling technique that interpolates and approximates the response surface across all data points. It has evolved into an important and powerful tool for interpolating sparse data with high accuracy [15]. in addition, RBF can be effective in the global optimization of costly functions for simulation-based designs [15].

Considering n distinct points $x_1, x_2, \dots, x_n \in \mathbb{R}^d$ where the function value is known, the interpolation form of the radial basis function is given by:

$$\boldsymbol{F}(\boldsymbol{x}) = \sum_{i=1}^{n} \boldsymbol{\lambda}_i \phi \left(\|\boldsymbol{x} - \boldsymbol{x}_i\|\right) + \boldsymbol{bx} + \boldsymbol{c} \quad (1)$$

There are two kinds of basic functions: parametric and non-parametric. Parametric functions can be used to improve the model's generalization properties:

- Multi-quadratic: $\phi(r) = \sqrt{r^2 + \sigma^2}$
- Gaussian: $\phi(r) = e^{-r^2/(2\sigma^2)}$
- Inverse multi quadratic: $\phi(r) = (r^2 + \sigma^2)^{-1/2}$

The following are the most commonly used non-parametric basis functions:

- Linear: $\phi(r) = r$
- Cubic: $\phi(r) = r^3$
- Fine plate spline: $\phi(r) = r^2 \ln(r)$

Solving the following system of linear equations in matrix form obtains the unknown parameters λ_i, b, et c of equation (1):

$$\begin{bmatrix} \boldsymbol{\Phi} & \boldsymbol{P} \\ \boldsymbol{P^T} & \boldsymbol{0} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\lambda} \\ \boldsymbol{a} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F} \\ \boldsymbol{0} \end{Bmatrix} \tag{2}$$

Where $\boldsymbol{\Phi}$ is the $n \times n$ matrix, with:

$$\boldsymbol{\Phi}_{ij} = \phi \| \boldsymbol{x_i} - \boldsymbol{x_j} \| \tag{3}$$

And,

$$P = \begin{bmatrix} 1 & x_1^T \\ 1 & x_2^T \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ 1 & x_n^T \end{bmatrix}, \quad \lambda = \begin{Bmatrix} \lambda_1 \\ \lambda_2 \\ \cdot \\ \cdot \\ \cdot \\ \lambda_n \end{Bmatrix}, \quad a = \begin{Bmatrix} a_1 \\ a_2 \\ \cdot \\ \cdot \\ \cdot \\ a_d \end{Bmatrix}, \quad b = \begin{Bmatrix} b_1 \\ b_2 \\ \cdot \\ \cdot \\ \cdot \\ b_d \end{Bmatrix}, \quad F = \begin{Bmatrix} F(x_1) \\ F(x_2) \\ \cdot \\ \cdot \\ \cdot \\ F(x_n) \end{Bmatrix} \tag{4}$$

Where d is the dimension of the vector x.

Equation (2) generates a unique vector and a, resulting in a unique metamodel capable of interpolating function values at any point in the design space. Because of its simple form, the radial basis function metamodel is simple to code and can be implemented in any programming language.

3.2 Elaboration of the basic metamodel

In the first step, a meta-model is built from the simulation results shown above. The radial basis function (RBF) method with the spline basis function is used to estimate the remaining values:

The following function is represented by the MATLAB model:

$$(St, u) = f(Th, F, E) \tag{5}$$

Where:

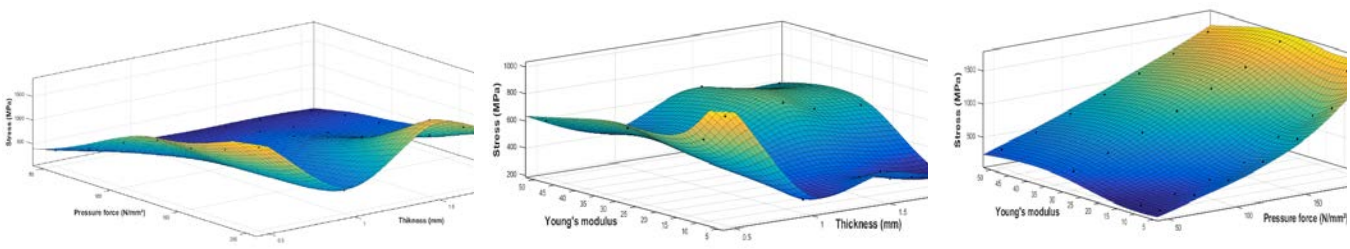
St: Stress, u: Strain, Th: Thickness, F: Pressure force, E: Young's Modulus.

The stress and strain variation surfaces are depicted in the figures below as a function of thickness, strength, and young's modulus. To demonstrate this 5D function, we will do the following:

(a): Plot the variation in stress and strain as a function of thickness and force when the young's modulus is constant;

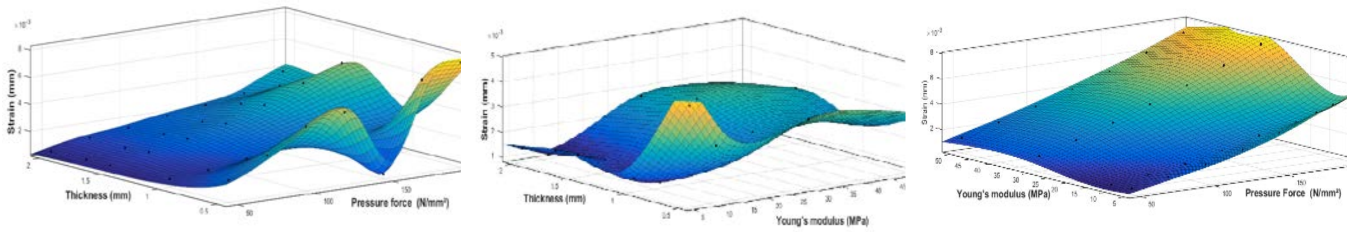
(b): Plot the surface stress and strain variation as a function of thickness and young's modulus when the pressure force is constant.

(c): Plot the surface of stress and strain variation as a function of pressure force and young's modulus with the elastic part's thickness constant.



(a): Young's Modulus is constant (b): Pressure force is constant (c): Thickness is constant

Fig. 6. Stress variation surfaces as a function of thickness, Pressure force, and young's modulus



(a): Young’s Modulus is constant (b): Pressure force is constant (c): Thickness is constant

Fig. 7. Strain variation surfaces as a function of thickness, Pressure force, and young’s modulus

3.3 Test model

The MATLAB model is tested with a set of data values as input. The thickness values for the model test are shown in the figure below:

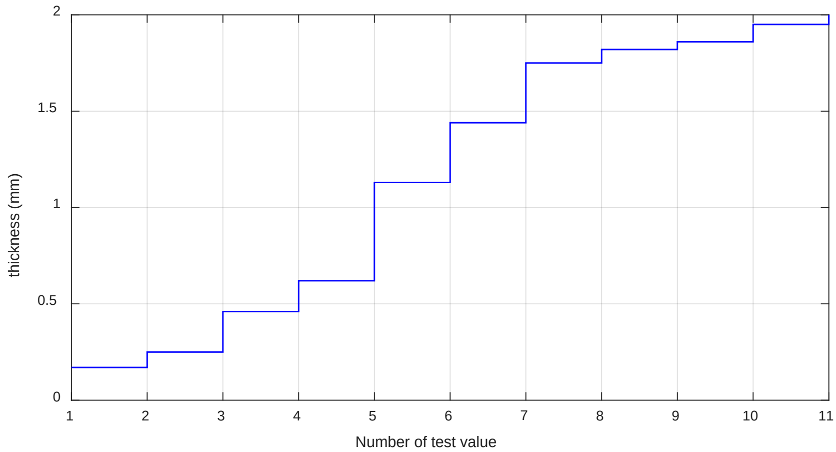


Fig. 8. Data values of the input thicknesses

The Young’s modulus and the pressure force are assumed to be constant, with values of E = 10MPa, and F = 75N/mm^2, respectively. The estimated stress and strain values are compared with simulation tests for each input value in the figures below.

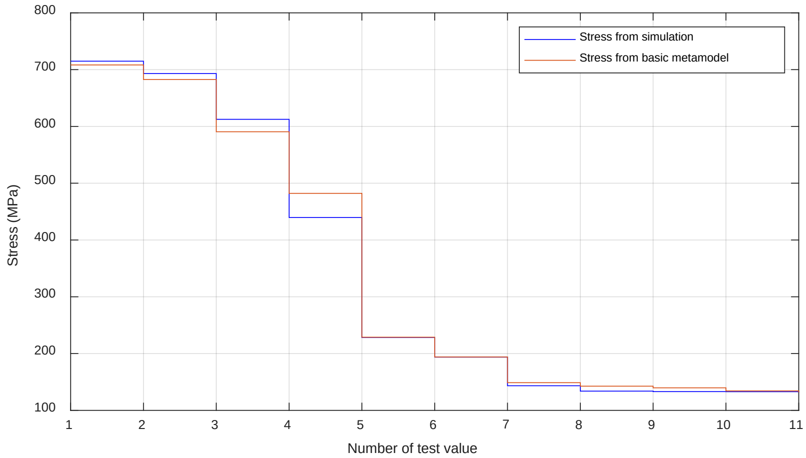


Fig. 9. Stress comparison of simulation and metamodel output

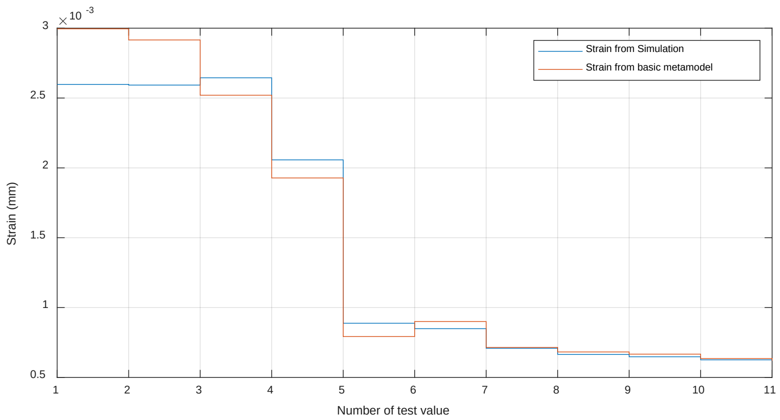
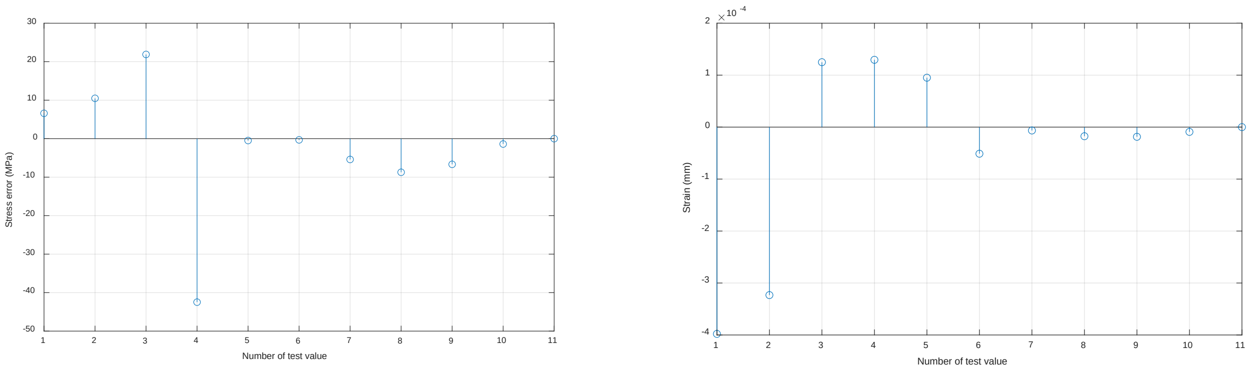


Fig. 10. Strain comparison of simulation and metamodel output

The figures above compare the behavior of the bolted structure estimated by the stress-strain metamodel with the results of a set of simulation tests performed using the input values shown in Figure 8. The comparison results show that the metamodel values follow the shape of the output curves, but there are discrepancies between the comparison values, suggesting that the metamodel needs to be strengthened in these areas. Adjustments to the metamodel data will be made by inserting new values from the simulations into the metamodel matrices to minimize the differences observed in these previous results. To illustrate the difference between the simulation results and the basic metamodel, Figure 11 shows the difference between the two curves.



(a): Stress error (b): Strain error

Fig. 11. Differences between the simulation results and the base metal model curve results

4 CORRECTION AND FITTING OF THE METAMODEL

The values approximated by the metamodel may differ from the numerical calculation result. Another adjustment or correction process is required to ensure the fidelity of the metamodel. The following figure illustrates this process:

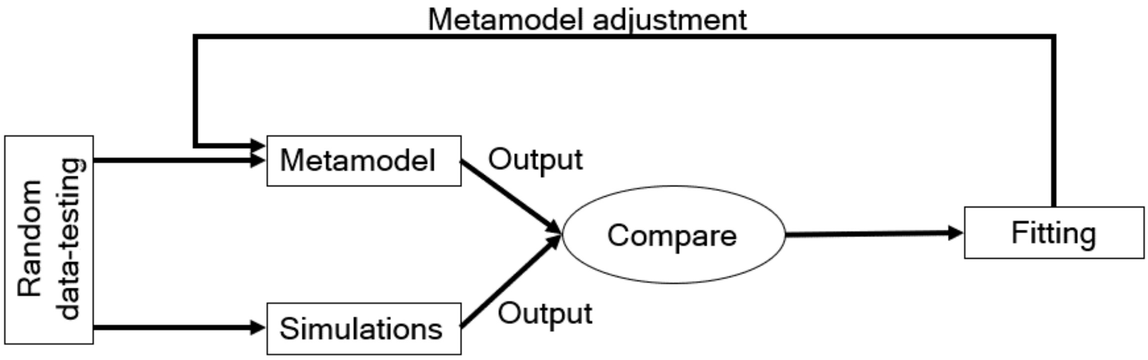
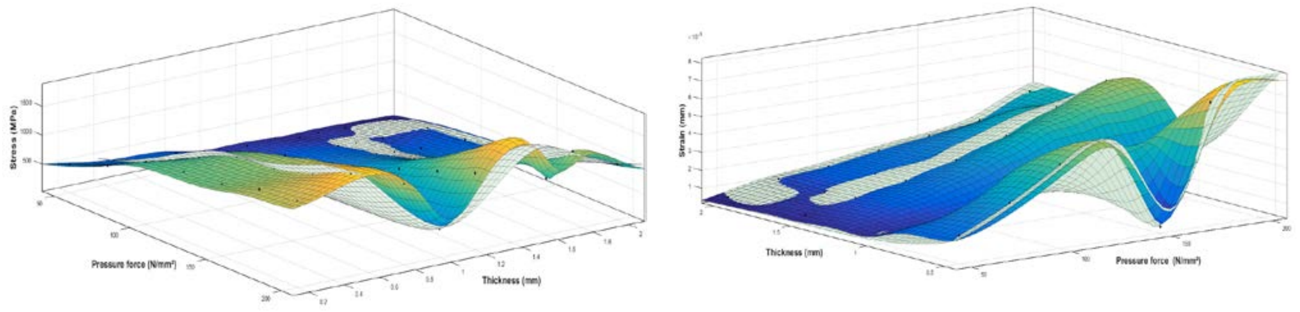


Fig. 12. Control and metamodel adjustment process

The proposed technique employs an iterative process in which a set of data values are inserted at the metamodel input and then used in simulation to compare the output data for the two tests. Then, for each input value, a comparator calculates the error rate between the metamodel and the simulation, and an update is performed by inserting the new values from the simulation into the metamodel matrices. Inserting new values adds new columns and rows to this metamodel matrix, which necessitates a quadratic approximation of these values. This procedure is repeated several times until the error is reduced to a tolerable level.



(a): Stress variation surfaces (b): Strain variation surfaces

Fig. 13. Comparison of the surfaces of variation of the outputs as a function of thickness, pressure force and young’s modulus between the basic metamodel and the adjusted metamodel

The grey areas represent the results of the basic metamodel, while the colored areas represent the results of the adjusted metamodel. The black dots represent the simulation values.

By comparing the two surfaces we can see that:

- The two surfaces have a similar shape in general, but the insertion of new points causes the appearance of new folds and deformations on the surface, which explains the structure’s level of non-linearity.
- The degree of variation increases as one moves away from the simulation points, which necessitates the addition of many points with an optimal distribution on the surface.

A test is run using the approach described previously to validate this process. Figures 14 and 15 depict the changes to the metamodel following the addition of the new results and approximations. To validate this process, a test is performed following the approach presented previously.

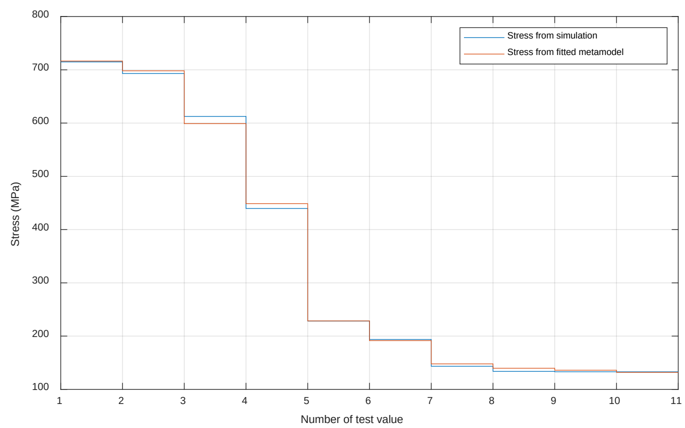


Fig. 14. Comparison between simulation and fitted metamodel stress results

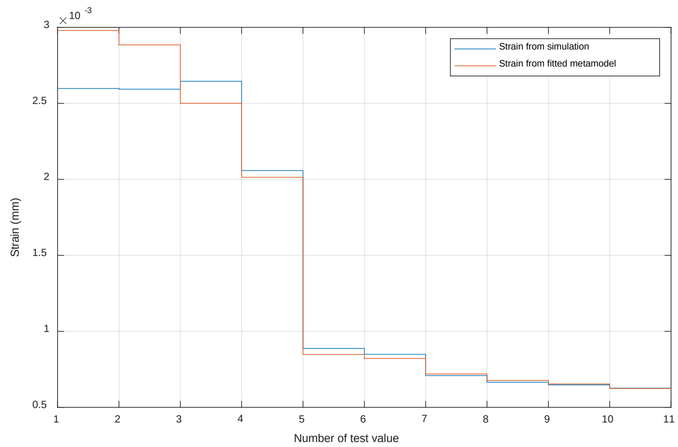
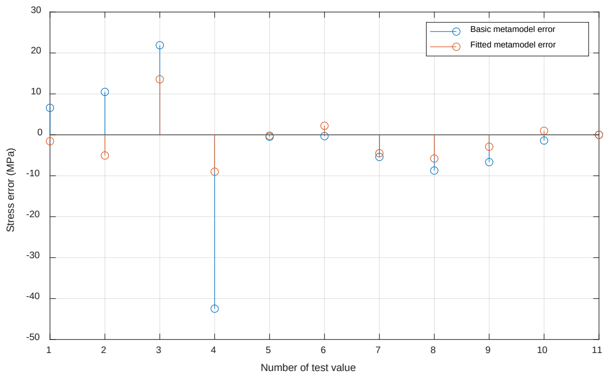


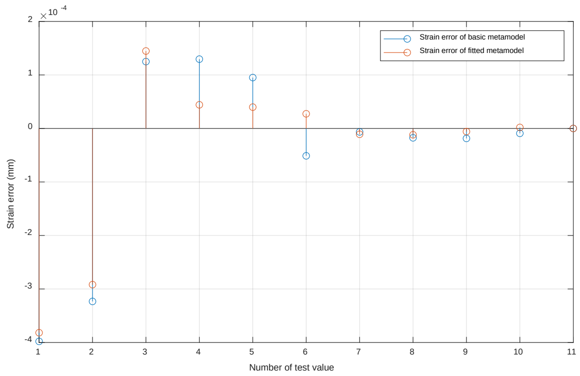
Fig. 15. Comparison between simulation and fitted metamodel strain results.

The figures above compare the behavior of the bolted structure estimated by the fitted stress-strain metamodel with the results of a series of simulation tests. The comparison results show that the metamodel values follow the shape of the output curve. They also show a significant reduction in the gap between the compared values, which indicates that the metamodel reinforced with multiple input values approximates the experimental numerical simulation results in a remarkable way by taking advantage of the computational gain by the metamodel.

Figure 16 depicts this improvement in comparison error by representing the difference between the basic metamodel error and the fitted metamodel error.



(a): Stress error



(b): Strain error

Fig. 16. Difference between the basic and fitted metamodel errors

The error of the fitted metamodel forced by many inputs is much smaller than that of the basic metamodel, as shown in Figure 16, demonstrating the usefulness of fitting to obtain approximate outputs (stresses and strains) of the experimental numerical simulation results while optimizing the computational cost.

5 CONCLUSION

In this paper, we present a tool for estimating the behavior of a strongly nonlinear structure (bolted structure with an elastic part), which was developed using a metamodeling approach. To accomplish this, we first conducted an experimental numerical simulation to investigate the evolution of Von Mises stress and strain in a bolted structure with an elastic part in the connection area. This experiment involves varying the input data (mechanical actions, joint thickness, and material) to investigate their effects on the evolution of the output data (Von Mises stress and strain). The results of this experiment differ; the presence of the joint, regardless of its thickness, material, or mechanical actions, allows concentrating the Von Mises stresses on the lower plate at the level of the assembly zone; it also allows for a large deformation of the elements located beside the hole in comparison to the other elements of the same plate. Afterwards, the data collected from the simulation was used to construct a metamodel using the radial spline basis function method, which was then used to develop tools for estimating stresses and strains as a function of changes in the input data. Finally, to ensure fidelity, to minimize the error between the metamodel and the simulation results, to obtain approximate results and to reduce the time calculation cost to 2 seconds, an adjustment and correction process is used.

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