UDC 539.4

Three-Dimensional Finite Element Analysis of Tensile-Shear Spot-Welded Joints in Tensile and Compressive Loading Conditions

H. Adib, J. Jeong, and G. Pluvinage

Laboratoire de Fiabilité Mécanique, Université de Metz-ENIM, Metz, France

УДК 539.4

Трехмерный конечноэлементный анализ точечных сварных соединений в условиях растяжения и сжатия

Х. Адиб, Ж. Жеонг, Г. Плювинаж

Университет г. Мец, Франция

Выполнен трехмерный конечноэлементный анализ образцов с одним, тремя и пятью точечными сварными швами при растяжении и сжатии. Для расчета на прочность используется распределение упругопластических напряжений в корне точечного шва. Предложена методика субмоделирования, позволяющая получить более точные результаты конечноэлементного расчета точечных швов малых размеров. Схема численного расчета дает возможность учитывать параметры материала и геометрические нелинейные эффекты, обусловленные наличием зазора между тонкостенными пластинами, их выпучиванием и т.д. Проанализировано упругое и упругопластическое поведение образцов с различной конфигурацией сварных швов при нагружении растягивающими и сжимающими осевыми усилиями.

Ключевые слова: трехмерный конечноэлементный расчет, соединения с точечной сваркой, методика конечноэлементного субмоделирования, тонкие пластины, зазор, выпучивание.

Introduction. Spot welding is one of the most practical and reliable methods for fixing thin metal sheets together. One of the desirable characteristics of spot welding techniques is its application in robotization. Hence, spot welds are widely applied to produce thin sheet components, especially in the automotive and transport industries. Fatigue is one of the critical problems in the design of spot welds. The required local stress and strain parameters in welded joints are commonly obtained via calculation, measurements and experimental based results [1]. The local stresses, in turn, induce stress concentration, which can be assessed using plate or shell model assumptions. Alternatively, finite element methods (FEM) are used for local stress-based fatigue prediction, e.g., using the Neuber [2], the Molski–Glinka [3–4], the volumetric approach [5–6], etc.

Three-dimensional finite element (3D FEM) stress analysis is applied to the most spot-welded joints, including tensile-shear, cross tension and peel-coal ones [7–12]. In this study, elastic-plastic 3D FEM analysis is applied to modeling of the mechanical behavior of mono point, triple points and multiple points in tensile-shear spot welds. The gap effects between two thin sheets are accounted for and compressive behavior of spot-welded joints is investigated.

To take into account spot welds, which are generally very small relative to other dimensions of welded joints, the main problems are a small sheet thickness and existence of stress concentration at the edges of nuggets, which are very sensitive to geometrical dimensions of spot welds (i.e., nugget diameter, small sheet thickness, etc.) To obtain exact and reliable distribution of the local stresses and strains at spot welds in three-dimensional case is usually very difficult due to a specific geometrical configuration of these spots. Hence, many assumptions based on application of beam elements, shell elements and combination of these two elements are proposed. For example, plate strip model, continuous beam model, combination of shell and solid elements for thin plates and nuggets, respectively [13], and application of a single beam [14] can be considered as the most practical methods (Fig. 1).

The most reliable and exact methods for determination of stress distribution in tensile shear spot welds are restricted to 3D FEM analyses.

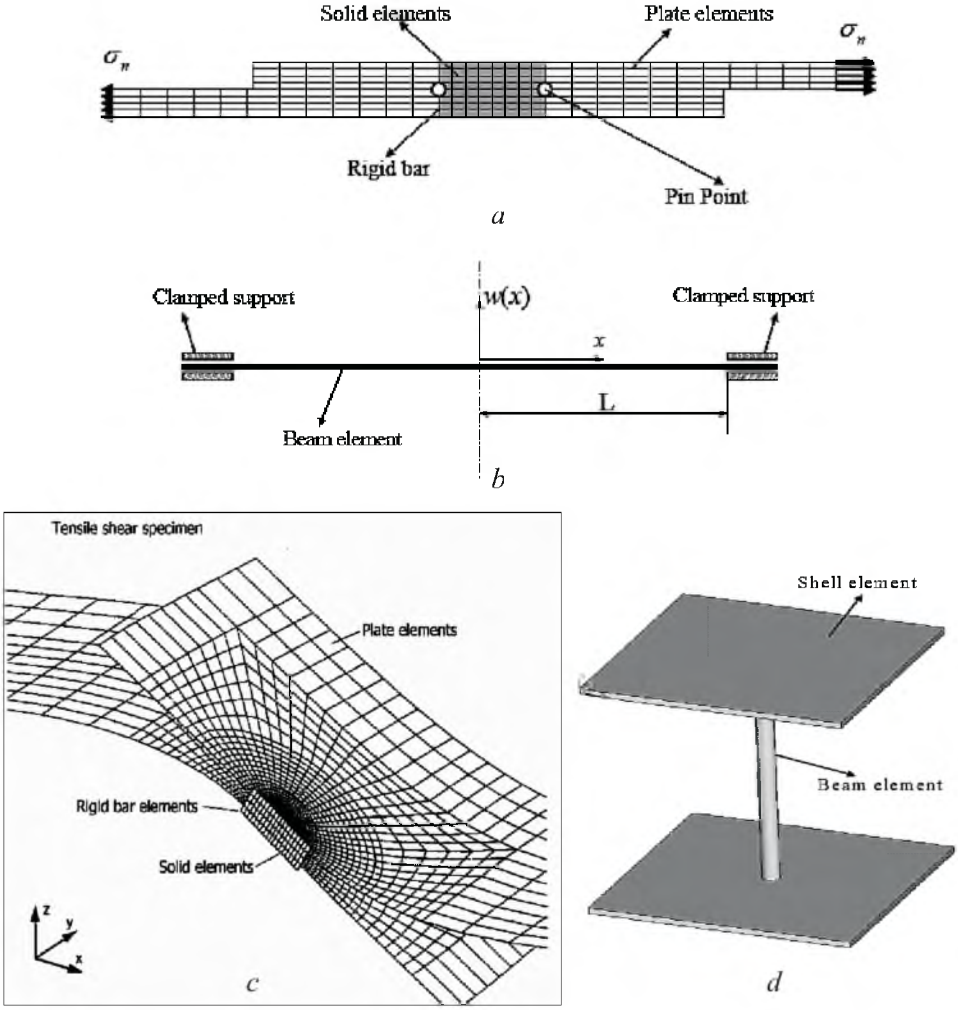


Fig. 1. Finite-element models for a mono-point-spot-welded joint: (*a*) plate strip model for tensile-shear spot welds; (*b*) continuous beam assumption; (*c*) application of shell, rigid bar, and solid elements for tensile-shear spot welds; (*d*) beam and shell element in vertical direction.

1. **Finite Element Model Description**. We perform FEM analysis for three specimen configurations involving a mono point, triple points, and multiple points spot-welded joints (Fig. 2). Due to symmetry, only one-half of spot-welded joints is considered. Solid elements with 20 nodes are used, and the ANSYS software is applied for linear and nonlinearcalculations. One end of specimens is fixed, while the other end is loaded in longitudinal direction of spot-welded joints by tensile or compressive loads. FEM analysis takes into account the material and geometrical nonlinear behavior of mono point spot-welded joint, which leads to their large-scale rotation displacements in their deformed shapes [13]. For triple and multiple point cases, the rotation phenomenon is less manifested, and thus the geometrical non-linearities can be neglected.

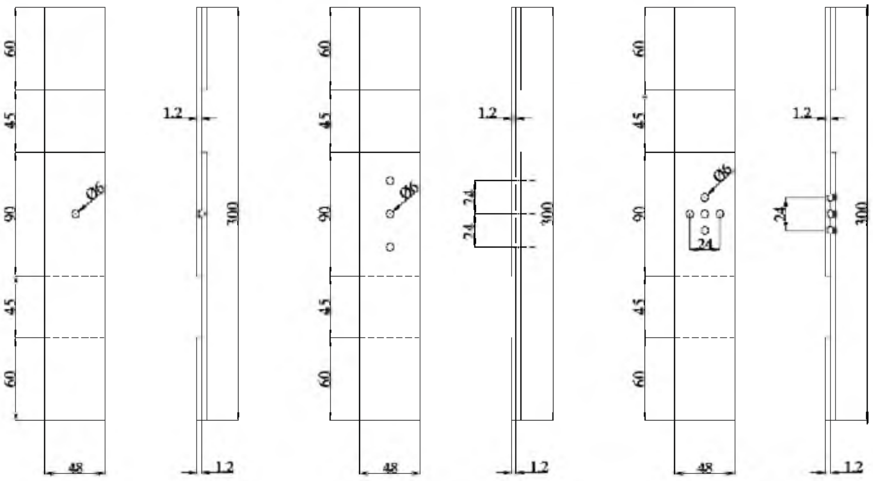


Fig. 2. Geometrical configuration of mono point, triple points and multiple points tensile-shear spot-welds left to right, respectively. (All dimensions are in mm.)

To obtain more realistic and reliable FEM analysis, it is critical to know the actual material properties and behavior. The cyclic stress–strain curve, which contains stiffening and hardening features of material, is very suitable for stress calculation via FEM analysis. The stress–strain curve for the material under study is shown in Fig. 3 [15].

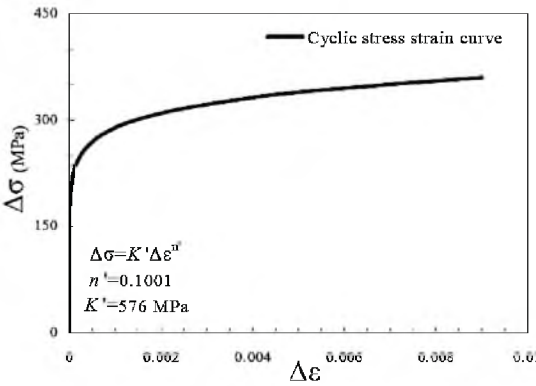


Fig. 3. Cyclic stress–strain curve and the material parameters: cyclic strain hardening exponent and coefficient n' and K', respectively.

The material properties are: Young's modulus $E = 205{,}000$ MPa, Poisson's ratio $\nu = 0.28$, yield stress $\sigma_Y = 299$ MPa, and the ultimate stress $\sigma_u = 431$ MPa. As seen from Fig. 2, the nugget is very small relative to the specimen length and width. Therefore we use a sub-modeling technique, in order to obtain the local stresses and strains at the nugget edge. In Fig. 4, the typical mesh and geometrical dimensions of the spot weld incorporated into the sub-modeling method are presented.

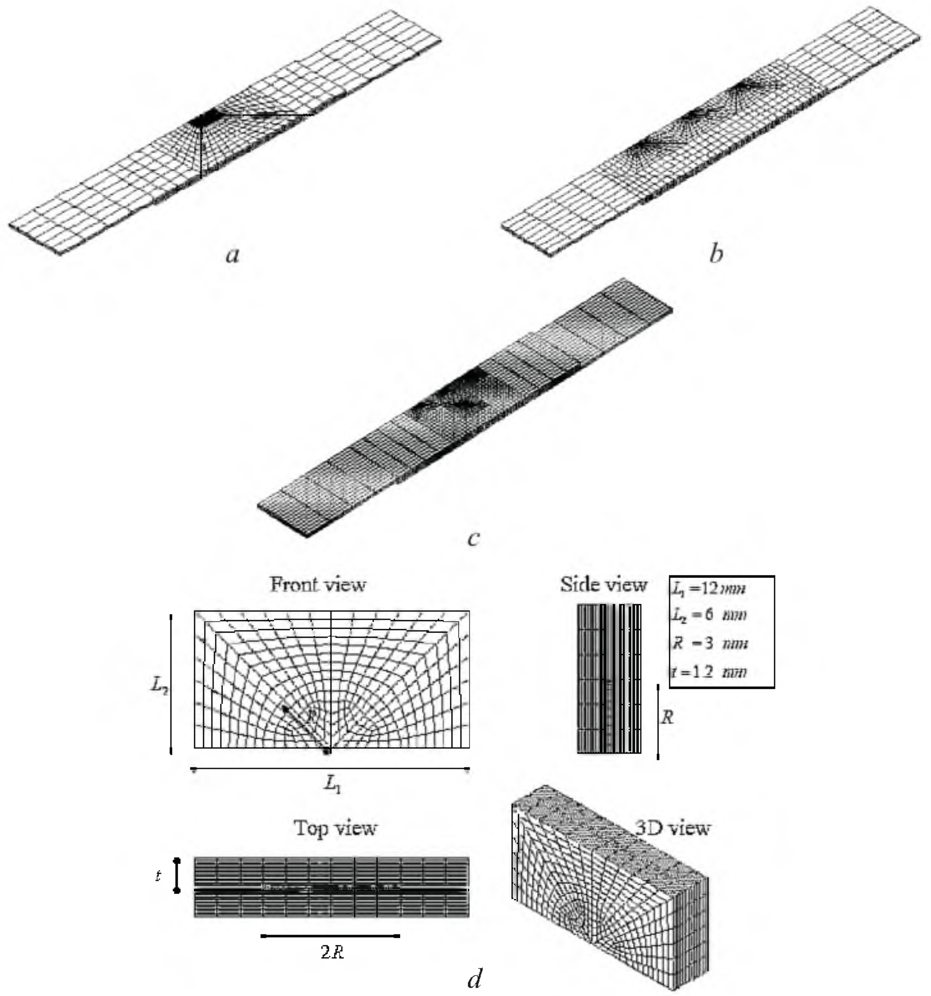


Fig. 4. General configuration of the FEM models: mono point (*a*), triple point (*b*), and multiple point (*c*) spot-welded joints, and detailed view of the spot weld (*d*).

2. **Application of Sub-Modeling Method in Spot-Welded Joints**. The sub-modeling technique overcomes the scale difference problems, discussed in the prevoius sedction and thus makes possible to get more accurate results in the required region of the FEM model. The cut boundaries for sub-modeling technique are presented in Fig. 5. These should be located far enough from the stress concentration zone, i.e., radii of the cutting boundaries for spot welds should be twice higher than that of a nugget. Sub-modeling reduces, or even eliminates, the need for sophisticated transition regions in solid FEM models and

allows one to optimize mesh density of the required region. However, sub-modeling applications are restricted to solid element models and cut boundaries' distances from the stress concentration zones. The cut boundaries need to be far enough from the hot-point stress zones, otherwise considerable errors in FEM results for considered models are likely to be obtained. Therefore, it is necessary to provide the comarative analysis of stress distributions obtained for the cut boundaries using the sub-model and the full-sized model and check the calculation accuracy. The cut boundary planes for tensile-shear spot-welded joint are shown in Fig. 5. The respective stresses calculated for the full-sized model and sub-model with the above the cut boundaries are presented in Fig. 6.

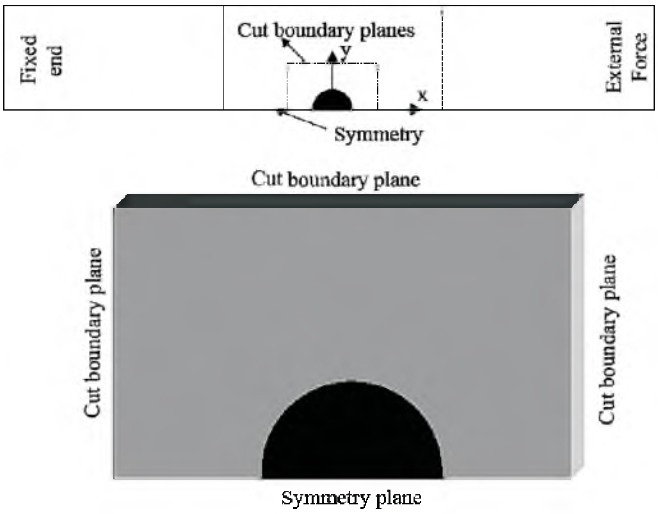
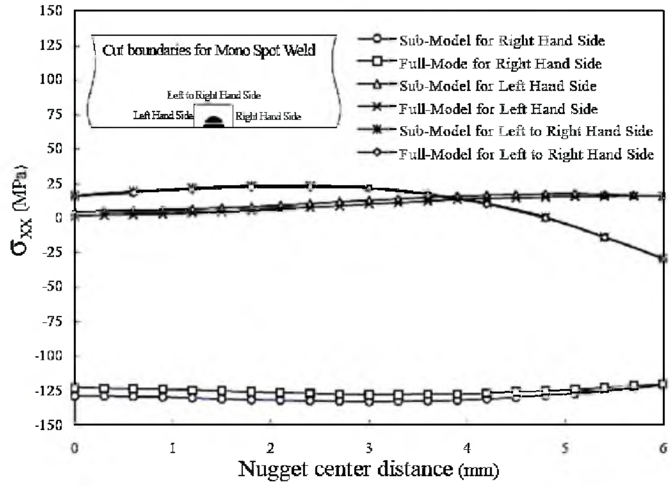


Fig. 5. The general configuration of cut boundary planes for tensile-shear spot-welded joint.

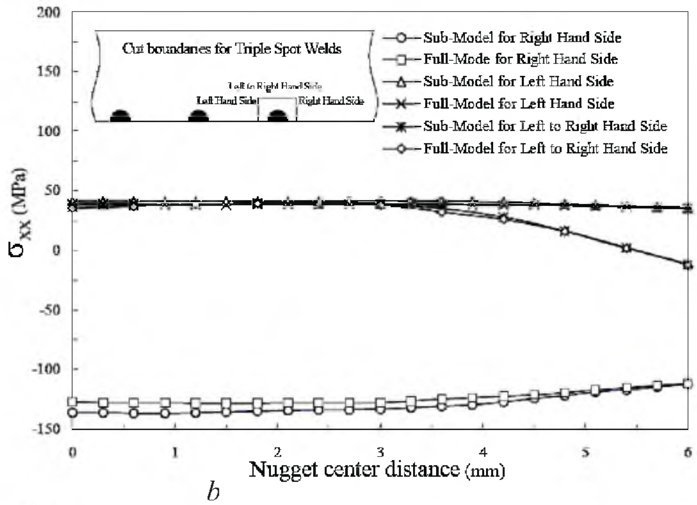
The comparative analysis of three tensile shear spot welds, including mono point, triple points and multiple points (see Fig. 6) demonstrates that the sub-model has a suitable accuracy and its cut boundaries are located far enough either from the high level stress locations and the hot points. Hence, the application of sub-modeling is expedient for the reliable analysis of the stress concentration zone near the spot-weld edges.

3. **Stress Distribution near Spot Welds in Tensile Shear Spot-Welded Joints**. The stress distribution for tensile shear spot-welded joints is the basis of spot weld design. Figure 7a presents the basic diagram of spot weld stress analysis: the stress values are given for left to right direction of spot welds. Figure 7b shows the distribution in thickness direction of stresses, which are generated as a combination of bending and tensile stresses at the edge of spot welds.

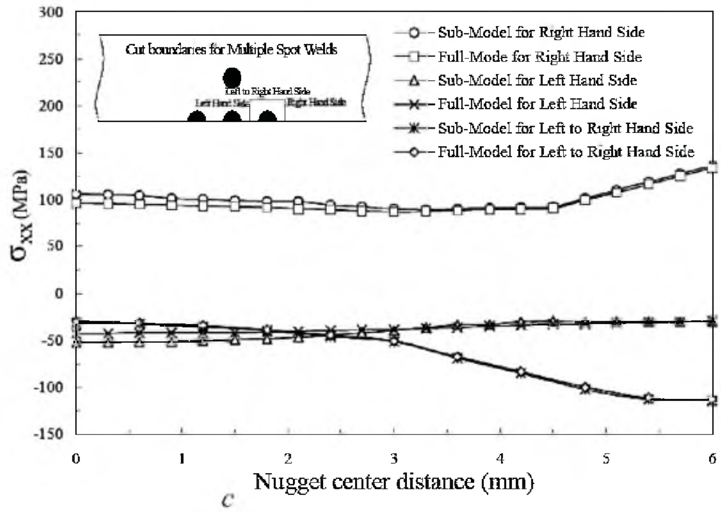
The stress distribution in longitudinal direction of spot welds for three tensile-shear spot welds, which is presented in Fig. 8, can be subdivided into three zones. Zone *I* covers the stress evolution in the lower plate, while zone *II* and zone *III* correspond to the stress distributions in the nugget and upper plate, respectively. The peak stress locations are at the end of zone *I* and at starting point of zone *III*.



a



b



c

Fig. 6. Comparative analysis of elastic stress distributions calculated by the sub-model and full-sized model for mono point (*a*), triple point (*b*), and multiple point (*c*) spot-welded joints.

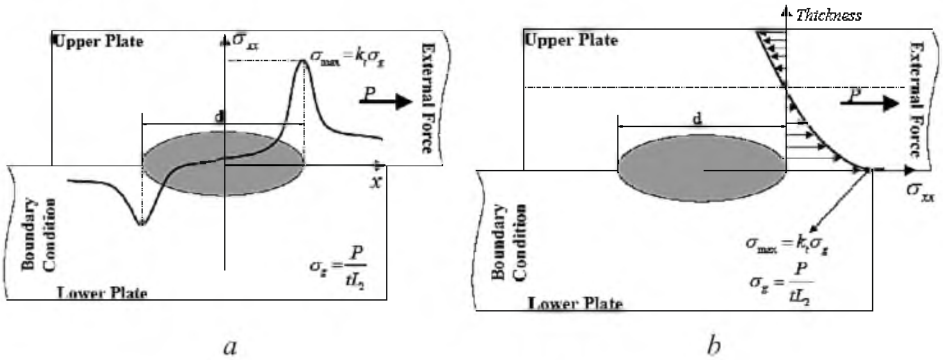


Fig. 7. The typical stress distribution near spot welds: (*a*) stress distribution in longitudinal direction for upper plate and lower plate as anti-symmetric form; (*b*) stress distribution in plate thickness direction (k_t is elastic stress concentration factor, σ_{max} is the maximum stress, and σ_g is the net stress).

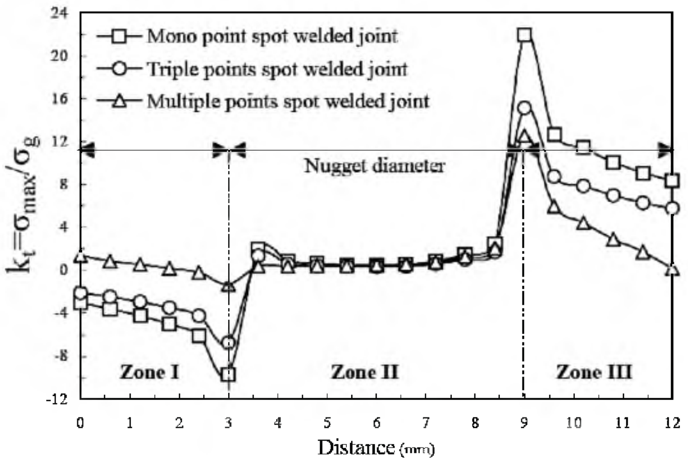


Fig. 8. Elastic stress concentration factor distribution near spot welds.

In Fig. 8, three types of tensile-shear spot-welded joints are compared. The elastic stress concentration factor k_t has two tensile and two compressive peaks. The comparative analysis of Fig. 8 reveals that triple points and multiple points exhibit a similar mechanical behavior, whereas addition of two more spot welds (multiple points) yields no high strength improvement as compared to triple points. Moreover, stress values in the boundary condition at the edge of a spot weld are less than the respective loads applied to the opposite side. Therefore, failure always occurs from the side where the load is applied. The stress distribution in thickness direction of thin plates is also critical. The initial cracks are formed at the edge of spot welds. In plate thickness direction, stress evolution depends on two major factors: 1) tension and 2) bending effects. The bending stresses are generated because of eccentricity, which naturally exists in these kinds of connections. Evidently, the tensile-shear spot-welded joints bending stresses depends on the applied forces, sheet thickness and gap between two thin plates. In Fig. 9, stress distribution in thickness direction is shown. High stress values are formed at the edge of nugget, and the stresses change their sign to negative at the neutral axis in plate thickness direction.

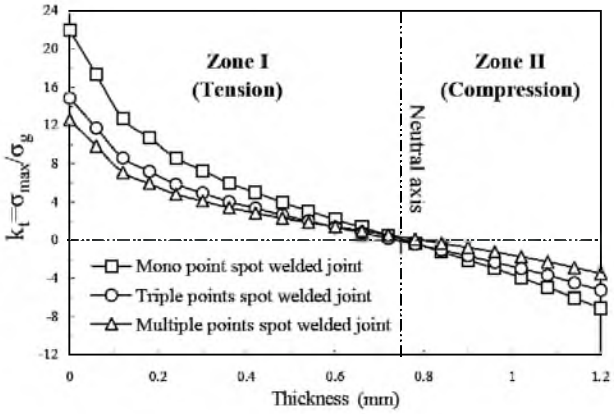


Fig. 9. Elastic stress concentration factor evolution along plate thickness direction from inner side to upper side for spot-welded joints.

Noteworthy is that the strength of spot welds plate thickness direction is controlled by the gap between lower and upper plates. Insofar as the ratio between the gap and the plate thickness is considerable even for a small gap, the latter cannot be neglected in the stress analysis and design. Incorporation of gap effects in FEM finite element models make a great difference in design of spot welds. Figure 10 shows the gap effect for mono point tensile shear spot-welded joint.

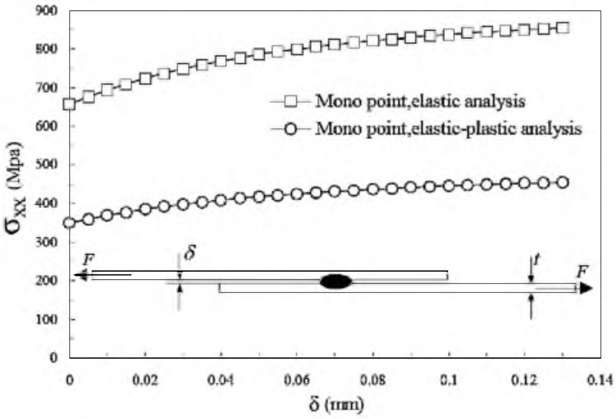


Fig. 10. The maximum structural stress evolution for elastic and elastic-plastic analysis due to gap variation in mono spot-welded joint case ($M = F(t+\delta) = Ft(1+\delta/t)$).

Hence, consideration of gap is essential for the estimation of fatigue strength of tensile-shear spot welds, although it is neglected the most researchers, e.g., [8–12]. Incorporation of the gap parameter δ in our 3D FEM analysis of tensile-shear spot-welded joints has revealed that this effect is the most pronounced in the case of mono spot-welded joint. In the current study the gap value is 0.12 mm and all calculations are based on experimental observation of selected specimens. As the stress distribution around spot welds is elastic-plastic, the cyclic stress–strain curve is used for calculations. As seen from Fig. 11, the stress relaxation in plastic zones near high stress location occurs, and σ_{max} depends on the elastic-plastic stressed state.

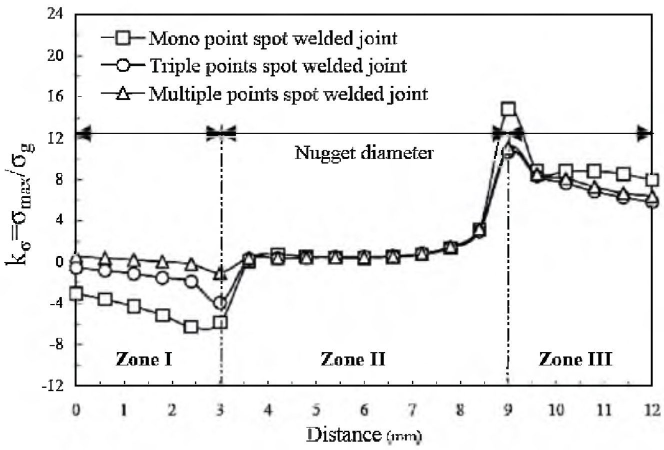


Fig. 11. Fatigue stress factor elastic-plastic distribution near spot welds in longitudinal direction. (The applied force for all spot-welded joints is taken as $F = 2250$ N.)

The elastic-plastic stress distribution in sheet thickness direction is given in Fig. 12.

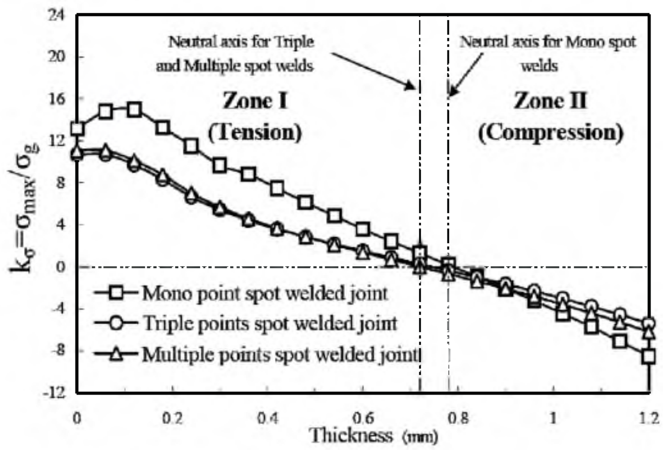


Fig. 12. Fatigue stress factor elastic-plastic distribution near spot welds in longitudinal direction. (The applied force for all spot-welded joints is taken as $F = 2250$ N.)

Here the same pattern as in the elastic case is observed: There are peak stresses as well, and tensile stresses change into compressive ones. However, in the elastic-plastic case, the neutral axes of triple and multiple spots approximately coincide, while mono spots are characterized by a larger tensile zone.

4. **Compressive Loading Conditions for Tensile-Shear Spot-Welded Joints**. The spot welds are generally applied for connection of two thin plates. Due to small thickness of these joints, their applicability is restricted to certain specific cases. The mechanical behavior of tensile-shear spot-welded joints under compressive loading conditions is critical for estimation of their application range. However, mostly tensile loads are currently accounted for in the application of spot welds (e.g., in automobile industry, for many types of thin sheet connections). In operational conditions, compressive loads can be experienced by spot-welded structures. Therefore, the buckling effect can occur in

tensile-shear spot-welded joints. We took this effect into account in the present 3D FEM analysis. Due to similarity between fixed-fixed ends and all the joints under study, this type of buckling is modeled in order to estimate that of tensile-shear spot-welded joints (Fig. 13).

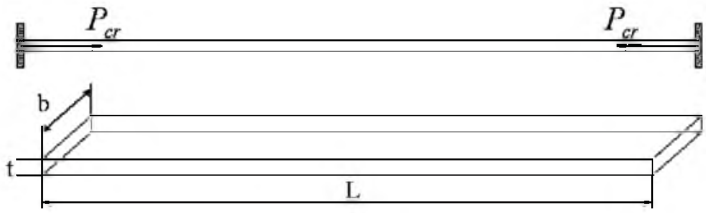


Fig. 13. Schematic representation of critical buckling load for fixed-fixed ends (L, b, and t are the plate length, width, and thickness, respectively; $P_{cr} = \dfrac{\pi^2 EI}{(0.5L)^2} = \dfrac{\pi^2 Ebt^3}{3L^2}$).

It is evident from Fig. 14 that the first buckling mode is the most typical for all three spot-welded joints under study.

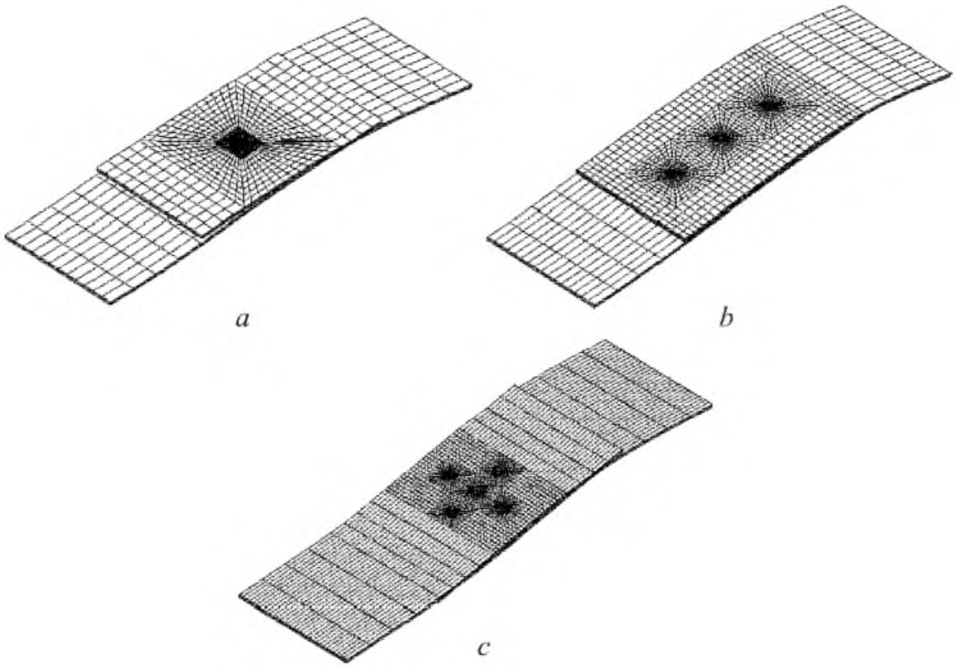


Fig. 14. The first buckling mode configuration for mono point (a), triple point (b), and multiple point (c) tensile-shear spot-welded joints.

The critical buckling loads for the three tensile-shear spot welds obtained from the 3D FEM analysis using the ANSYS software are summarized in Table 1. It is noteworthy that the critical buckling load for fixed-fixed ends can be easily calculated using the available input data [16–17].

As seen from Table 1, all spot-welded joints under study have a higher buckling resistance tant a plate with fixed-fixed end conditions, but the critical buckling load capacity for triple points is the highest. The major parameter in buckling analysis is geometrical characteristics. The comparison between triple and multiple points spot-welded joints in Fig. 2, indicates that the distance between triple joints in longitudinal direction of spot-welded joint is two times relative to multiple-points. Due to this geometrical effect, unbraced distance for triple points is less than multiple points spot-welded joints. Hence, the major geometrical parameter, which has a great effect in buckling capacity of spot welds can easily be distinguished. Other parameters such as plate thickness, nugget diameter and number of spot welds is also important to verify compressive behavior of tensile-shear spot-welded joints, but the most effective geometrical parameter in buckling capacity of spot welds is distance between spot welds or unbraced distance. In Fig. 15, the braced and unbraced distances for buckling capacity analysis are shown.

T a b l e 1

The Critical Buckling Load and Effective Length for Three Different Types of Spot-Welded Joints

Spot-welded joint type	P_{cr}, N	$KL=\sqrt{\dfrac{\pi^2 EI}{P_{cr}}}$, mm	K
Fixed-fixed ends	636.71	150.00	0.5000
Mono point	866.85	128.55	0.4285
Triple points	1203.92	190.08	0.3636
Multiple points	1025.59	118.18	0.3939

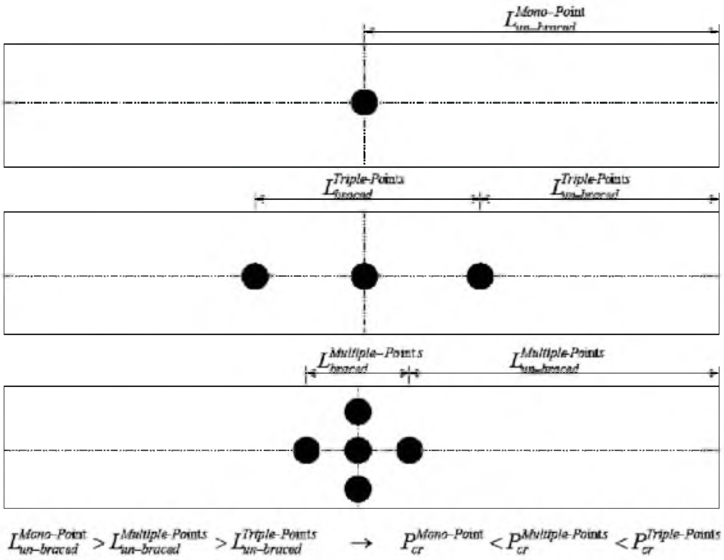


Fig. 15. Braced and un-braced length for three spot-welded joints (mono point, triple points, and multiple point's tensile-shear spot-welded joints).

The braced and unbraced distances are very important to manipulate compressive behavior of spot-welded joints, and it is shown in Table 1 that the number of spot welds improves the buckling capacity of tensile-shear spot-welded joints, while the unbraced length augmentation results in a lower buckling capacity. Although multiple spot-welded joints have two additional spot welds, their buckling capacity is less than that of triple ones. This can be attributed to the unbraced and braced length effects. The distance between spot welds in tensile behavior is also important, but manifests a different behavior pattern. The braced length in all spot-welded joints provides a rigid section and if the braced length is long, the rigid section increases, which require higher force values to obtain the buckling conditions. Hence, the lowest buckling capacity can be expected from mono point spot-welded joints. And the highest one – from lap welded joint.

In addition to the buckling effect, we have studied the post-buckling behavior of spot welds. The nonlinear buckling analysis is required to investigate the post-buckling conditions of all three mentioned spot-welded joints. The rotation of spot welds is the most critical parameter in their post-buckling analysis. In Fig. 16, the post-buckling behavior of three selected spot-welded joints is shown. Here the angle between two thin sheets (2θ) changes with the compressive axial load.

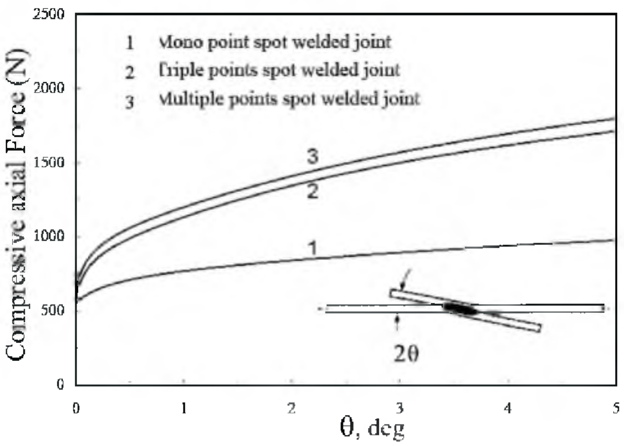


Fig. 16. Post-buckling analysis of selected tensile-shear spot-welded joints with the same spot weld configuration.

As seen from Fig. 16, the rotation of mono point spot-welded joint occurs even at low compressive loads. Hence, joint rotation based on compressive loads for mono spot-welded joints is more noticeable. The experimental results for tensile-shear spot welds demostrate the same pattern [18]. The triple and multiple points produce less pronounced joint rotation as compared to the mono points, which can be related to the respective number of spot welds and their locations.

5. **Fracture Mechanics Applicability to Spot-Welded Joints**. The results obtained from this study suggest that tensile-shear spot-welded joints exhibit different mechanical behavior in tension and compression. The spot-welded joints study can be subdivided into low-cycle fatigue (LCF) and high-cycle fatigue (HCF). The crack initiation and propagation occur in the heat-affected zone (HAZ) and base metal within the LCF and HCF ranges, respectively. Low axial loads correspond to the HCF range and, consequently, cracks initiate and propagate in the HAZ. Alternatively, high axial loads lead to initiation and propagation of cracks in the base metal, which makes possible application of the

fracture mechanics to tensile-shear spot-welded joints. Various formulas for the stress intensity factors in such joints have been derived [19–21]. However, the available fracture mechanics approaches and SIF formulas for spot-welded joints are not applicable to crack initiation in the HAZ and for the LCF analysis [22–23]. Therefore, the proposed elastic-plastic 3D FEM analysis can be used as a tool of further expansion into this field.

Conclusions

1. Three-dimensional mechanical behavior of tensile-shear spot-welded joints has been studied for three spot-welded joint types, including mono point, triple points and multiple points. FEM solutions of stress fields in the spot welds are obtained for elastic, elastic-plastic, buckling and post-buckling loading cases. The application of sub-modeling technique yielded more accurate and less time-consuming numerical results than conventional FEM meshing schemes.

2. The stress distributions near spot welds in longitudinal and thickness directions have been analyzed, the critical point being the toe of spot welds. The mono point case, due to its specific configuration and a large plastic zone, exhibits a high joint rotation and a complex deformation pattern, while triple and multiple points produce less joint rotation and are more preferable for application from this standpoint.

3. The mechanical behavior of triple and multiple point spot-welded joints are very close to each other in tension and compression. Hence, they have similar strain and stress distributions, which suggest similar fatigue behavior. The stress distribution in thickness direction reveals that a combination of the axial stresses and bending stresses controls the stress distribution pattern and mechanical behavior of the joints under study. The gap existing in spot welds raises the stress concentration factor at the toe of spot welds. Low thickness of sheet metals has a significant influence on the stress distribution at spot welds. The gap effect results in a higher bending moment, and consequently, in higher tensile stresses and larger plastic zones, which reduce the fatigue life and load-bearing capacity of spot-welded joints.

4. The buckling capacity of spot-welded joints has been studied. The comparison between the chosen specimens and fixed-fixed end beam shows that the larger number of spot welds results in a higher buckling capacity of spot-welded joints, but such factors as braced and unbraced length play their role as well. Post-buckling behavior of spot-welded joints has also been studied and explained within the framework of the proposed approach.

5. Finally, such parameters as the number of spot welds, spot-weld diameter, plate thickness, distance between spot welds or braced distance and gap between two thin sheets are shown to be crucial for the reliable design of spot-welded joints. The special emphasis is made on the gap effects, which are neglected in recent publications, but are shown to deteriorate the mechanical behavior for spot-welded joints. Another aspect of this problem is development of an adequate model of processes in the heat-affected zone for the low-cycle fatigue life prediction of spot-welded joints.

Резюме

Виконано тривимірний скінченноелементний аналіз зразків з одним, трьома та п'ятьма точковими зварними швами в умовах розтягу і стиску. Для розрахунку на міцність використовується розподіл пружно-пластичних напружень у корені точкового шва. Запропоновано методику субмоделювання, що дозволяє отримати більш точні результати скінченноелементного розрахунку точкових швів малих розмірів. Схема числового розрахунку дає можливість враховувати параметри матеріалу і геометричні нелінійні ефекти, зумовлені наявністю зазору між тонкостінними пластинами, їх випинанням і т.п. Проаналізовано пружну і пружно-пластичну поведінку зразків із різною конфігурацією зварних швів при навантаженні розтяжними і стискальними осьовими зусиллями.

1. D. Radaj, "Theory of forces and stresses in spot-welded overlap joints," *Arch. Appl. Mech.*, **67**, 22–34 (1996).
2. H. Neuber, *Kerbspannungslehre*, Springer-Verlag, Berlin (1958).
3. G. Molski and G. Glinka, "A method of elastic-plastic stress-strain calculation at the notch roots," *Mat. Sci. Eng.*, **50**, 93–100 (1981).
4. G. Glinka, "Energy density approach to calculation of inelastic stress-strain near notches and crack," *Eng. Fract. Mech.*, **22**, 485–508 (1985).
5. G. Qylafku, Z. Azari, N. Kadi, et al., "Application of a new model proposal for fatigue life prediction on notches and key-seats," *Int. J. Fatigue*, **21**, 753–760 (1999).
6. H. Adib and G. Pluvinage, "Theoretical and numerical aspects of volumetric approach for fatigue life prediction in notched components," Ibid, **25**, No. 1, 67–76 (2003).
7. M. Fujimoto, N. Mori, and S. Sakuma, *Stress Distribution Analysis of Spot-Welded Joints under Tension-Shear Load*, International Institute of Welding, III-721-82 (1982).
8. T. Satoh, H. Abe, K. Nishikawa, and M. Morita, "A study on three dimensional elastic-plastic stress analysis of spot-welded joint," Proc. 4th Int. Conf. on *Fatigue and Fracture Thresholds* (15–20 July, 1990), Honolulu Hawaii.
9. D. Radaj, Z. Zhang, and W. Muhrmann, "Local stress parameters at the weld spot of various specimens," *Eng. Fract. Mech.*, **35**, No. 5, 933–951 (1990).
10. X. Deng, W. Chen, and G. Shi, "Three dimensional finite element analysis of the mechanical behavior of spot welds," *Finite Elem. Anal. Design*, **35**, 17–39 (2000).
11. W. Chen and W. Deng, "Performance of shell elements in modeling spot-welded joints," Ibid, **35**, 41–57 (2000).
12. H. Henryson and B. L. Josefson, "Fatigue crack initiation at spot welds fracture mechanics or strain life approach?," Proc. 7th Int. Fatigue Congress, *Fatigue 99* (1999), Vol. 2, pp. 1251–1256.

13. D. Radaj and S. Zhang, "Geometrically nonlinear behavior of spot-welded joints in tensile and compressive shear loading," *Eng. Fract. Mech.*, **51**, No. 2, 281–294 (1995).
14. Y. Zhang and D. Taylor, "Fatigue life prediction of spot-welded components," Proc. 7th Int. Fatigue Congress, *Fatigue 99* (1999),Vol. 2, pp. 1275–1280.
15. H. Adib, J. Gilgert, and G. Pluvinage, "Fatigue life duration prediction for welded spots by volumetric method," *Int. J. Fatigue*, **26**, No. 1, 81–94 (2004).
16. S. P. Thimoshenko and J. M. Gere, *Theory of Elastic Stability*, Second edition, McGraw-Hill, New York (1961).
17. W. F. Chen and E. M. Lui, "Structural stability," in: *Theory and Implementation*, Elsevier, New York (1987).
18. H. Adib, "The effect of geometry in spot-welded joints for fatigue life prediction," Internal Report of Laboratory for Reliability Mechanics, Metz University, 28 July 2000.
19. D. J. Chang and R. Muki, "Stress distribution in a lap joint under tension shear," *Int. J. Solid Struct.*, **10**, No. 5, 503–517 (1974).
20. L. P. Pook, "Approximate stress intensity factors for spot and similar welds," NEL Report 588, National Engineering Laboratory, UK (1975).
21. J. F. Cooper and R. A. Smith, "Initial fatigue crack growth at spot welds," Proc. Int. Conf. on *Fatigue Engineering Materails and Structures* (1986), Vol. 2, pp. 283–288.
22. H. Adib, PhD Thesis, University of Metz, France (2003).
23. N. Pan and S. Sheppard, "Spot welds life prediction with cyclic strain range," *Int. J. Fatigue*, **24**, No. 5, 519–528 (2002).

Received 05. 09. 2003