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A general formulation of an analytical model for the elastic–plastic behaviour of a spot weld finite element

Pierluigi Fanelli [a], Francesco Vivio [b,*]

[a] DEIM, University of Tuscia, Largo dell'Università, 01100 Viterbo, Italy
[b] Department of Enterprise Engineering, University of Rome "Tor Vergata", Via del Politecnico 1, 00133 Rome, Italy

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ABSTRACT

A general formulation of an analytical procedure for the evaluation of the elastic–plastic behaviour of spot welded joints is presented. The procedure is based on a model of spot weld region shaped by a circular plate having variable thickness and having a central rigid nugget representing the spot weld. A closed form solution of the original analytical approach allows to define the displacement of the rigid nugget, when an axial load is applied on the plate, though plasticity and large displacements are present. The so defined spot weld region model has to be used as the basis to extend the capability of a spot weld element in FE analysis when plasticity and large displacements are in effect. As well as presented in previous works, the procedure is completely general; the accuracy on geometrical parameters dependency is now improved and the strain hardening material characteristics has been introduced.

Furthermore the constraints influence of the sheet metal surrounding the spot on elastic–plastic behaviour is investigated and evaluated, in order to generalize the plastic contribution on spot weld stiffness. Even if the theoretical framework is non-trivial, the formulation of the proposed procedure is straightforward and it can be easily implemented as an add-on of a FE code.

The results, obtained by applying the general analytical procedure to some examples of spot welded joints, precisely match those obtained modelling spot weld region by FEA.

1. Introduction

The spot welding is the technology most widely used for joining metal sheets especially in automotive and railways applications; in these contexts the structures may contain several thousands of spot welds. Cause to the complex multi-axial loads passing through these spots under operation, the stress field close to the spot region is very complex, mostly due to geometrical irregularities and several local effects at the edge of the spot weld.

The correct evaluation of local stiffness of the spot weld and, more generally, of its structural behaviour requires an accurate modelling with finite elements of the region next to the spot, which is characterized by high stresses and local deformations; on the other hand, a reduced computational effort (even if the current computational capabilities available are significantly increased) is needed, particularly when analysis of actual multi-spot structures (with several spot welds) are performed. Then the objective is an accurate evaluation of the local stiffness of spot joints, introducing adequate modelling of the region close to each spot joint, which is fundamental to perform a reliable simulation of multi-jointed structures and, consequently, a good estimate of loads acting on spots.

The studies about junction behaviour are mainly focused on problems of fatigue cracks, or of plastic collapse. Fatigue life estimation has been investigated using different approaches. Generally, the main effort has been made to evaluate stresses at the joints, using complex FE models, theoretical approaches, experimental evidences or any combination of the above. Often, fracture mechanics has been used to evaluate stress intensity factors in natural crack or notch along the nugget circumference. In this case, various types of spot welded connections and different geometries of joint have been investigated using finite element models considering linear elastic material behaviour [1,2] or introducing approximate or completely analytical solutions for stress intensity factor [3–5]. It should also be noted that in these cases fatigue behaviour models are often only applicable and valid to reference joints of simple shape. Otherwise the use of a conventional stress parameter has been proposed [6–9] demonstrating its effectiveness to predict spot weld fatigue life. In this case, simple models can lead to a good estimation of the loads acting on the spot welds that can be related to a conventional

* Corresponding author. Tel.: +39 06 72597123; fax: +39 06 2021351.
E-mail address: vivio@uniroma2.it (F. Vivio).

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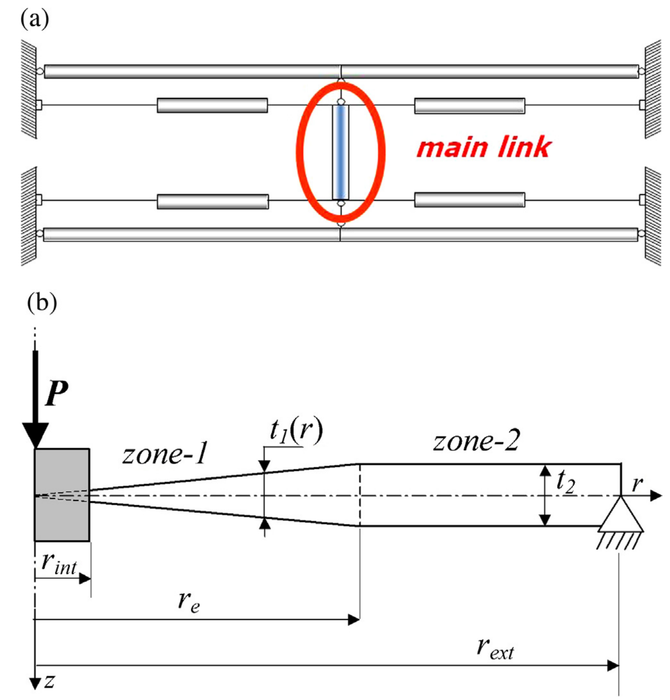

Fig. 1. Schematization of SWE (a) and equivalent circular plate with rigid inclusion (reference theoretical model) subjected to an opening load P (b).

stress parameter by analytical approximations [6,7] or theoretical models [8,9].

Nevertheless, in the processes of design and testing of many structures that use this type of joints, it is required that spot welds possess an high resistance capacity, particularly in exceptional operating conditions, such as crash, or in low cycle fatigue, where plasticity is present. However, the complications due to the occurrence of plastic flow, associated with such load conditions, and the difficulties inherent in the geometry of the element, make the problem difficult to solve with a theoretical approach. Its resolution is so complex that necessarily requires the use of numerical methods or experimental tests or, very often, the union of the two.

In order to obtain a progressive failure of the spot welds, it is desirable to have an optimal failure mechanism instead of others. The request is to maintain a sufficient rigidity for the whole of the energy absorption process in order to avoid a sudden fall in the capacity to absorb the impact loads. All automobile manufacturers who use these assembly techniques know perfectly well that if the structural optimal behaviour of a weld spot is provided, it will fail with a mechanism commonly referred to as 'nugget pull-out failure'. Some approaches to the problem were proposed in the past, which introduced various degrees of simplification replacing the spot weld with a single beam element [10–13]. This represents at the moment the only way to cope with simulating the global behaviour of structures with several spot welds, but at the same time precision is lost with regard to intermediate states of deformation and the correct evaluation of local stiffness of spot joints. In fact, in order to simulate the progressive failure of the spot

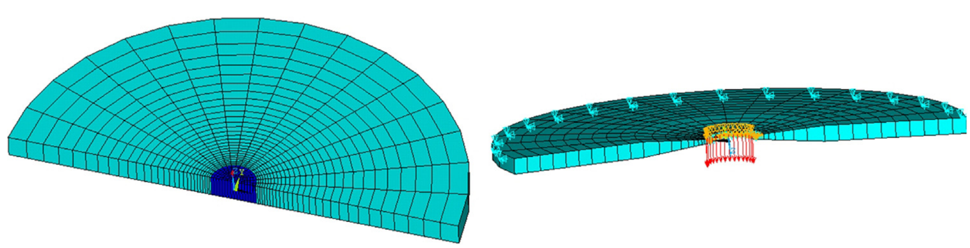

Fig. 2. FE models: sections of equivalent plate FE model (with variable thickness) and actual plate FE model (with constant thickness). Simply supported edge constraints are present at external radius and clamping constraints at internal one, where orthogonal load is applied.

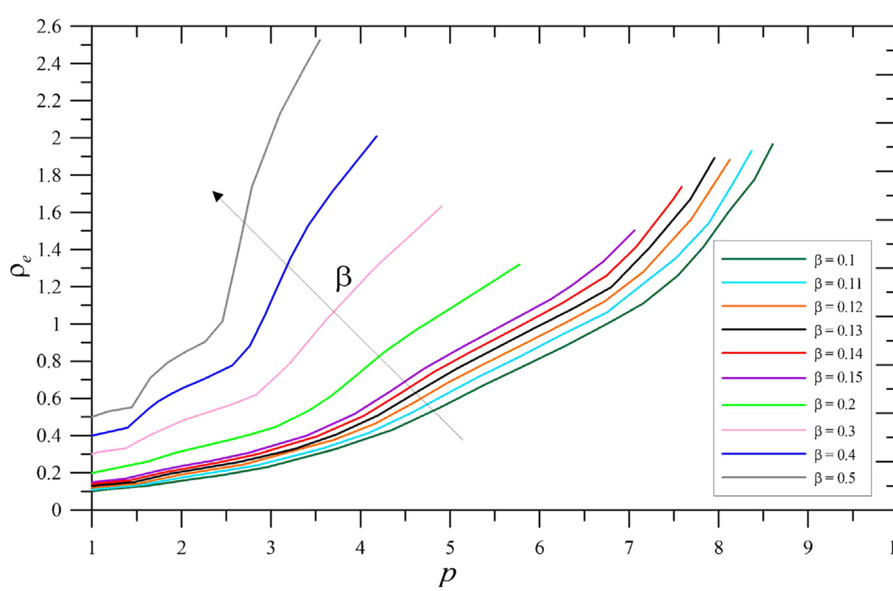

Fig. 3. Variation of dimensionless equivalent radius along dimensionless load for different values of dimensionless inner radius β; actual thickness $t = 2$ mm; outer radius $r_{ext} = 20$ mm; large deflections hypothesis.