Numerical and experimental contact analysis of a steel ball indented into a fibre reinforced polymer composite material

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A three-dimensional anisotropic contact algorithm has been developed to analyse the contact behaviour of metal–composite bodies. The elements of the influence matrix are obtained by coupled finite-element anisotropic models. Linear elastic and approximate elastic–plastic techniques can evaluate the contact parameters (the normal approach, the size of the contact area and the contact pressure distribution) following different failure criteria. The contact technique is applied to the problem of a steel ball indented into a polymer composite material having either normal or parallel unidirectional fibre orientation. Finally, the contact results are verified by experimental evaluations. The latter were obtained by the use of a static testing machine, a laser profilometer, an optical microscope and a scanning electron microscope, and they illustrate the real response of the composite structure subjected to ball indentation. Good agreement between both methods could be demonstrated.

1. Introduction
The ball indentation test is a well-known procedure to evaluate the strength properties of metals in both the elastic and the elastic–plastic range. In recent years, this test has also been applied to anisotropic composite materials, in particular to characterize their mechanical behaviour, e.g., with regard to their fibre–matrix interfacial shear strength. The interfacial failure due to the indentation test was studied by Carman et al. [1] using experimental and analytical techniques. Microstresses were evaluated by macroscopic and microscopic approaches and a cellular modelling concept. According to their experimental observations, substantial fibre–matrix interfacial failure was found to occur underneath the ball indenter. To analyse the ball–composite contact problem, they obtained a solution with a macroscopic and microscopic approach utilizing an elasticity solution to formulate the macroscopic solution. Using the macroscopic solution to generate local boundary conditions in conjunction with a microscopic solution based on a cellular model, they constructed approximate closed-form solution for the stress state in a microregion.

To solve anisotropic contact problems, transversely isotropic solutions were presented by Dohan and Zarka [2], Gladwell [3], Suemasu et al. [4], Svelko [5] and Ovaert [6]; in all these cases, the plane of isotropy was oriented normal to the plane of contact.

The aim of this paper is to present a new anisotropic contact algorithm for the case where a composite material, containing normal (N) or parallel (P) fibre orientation in the surface, is subjected to ball indentation (Fig. 1). The numerical contact algorithm follows the influence matrix approach (reviewed in [7]), while the anisotropic influence matrix is obtained by coupled finite-element (FE) models. The approximate coupling technique considers only the displacements along the coupled surfaces. While “multiscale” modelling [8] or the “global–local” analysis [9] techniques are more general procedures, the coupled solution provides a more realistic elastic deformation of the composite system in the vicinity of the contact area, and at the same time also the effect of the macrosystem is incorporated.

The numerical contact algorithm, developed initially for isotropic bodies having rough surfaces [10], takes into consideration the non-linear material behaviour of a composite structure, using an approximate approach.

The final aim of developing an anisotropic contact algorithm was to apply it for sliding contact analysis of metal–composite surfaces; in addition, effects of contact temperatures should be evaluated. For the FE analysis the COSMOS/M system (vl. 75) [11] was used.
The indentation problem was experimentally evaluated by measuring the force–displacement curve and by observing the indented areas using laser profilometry as well as optical microscopy and scanning electron microscopy (SEM).

The composite material (investigated under N and P fibre orientations) was a unidirectional continuous carbon fibre–poly(ether ether ketone) (PEEK) system, having a fibre volume fraction $V_f$ of 0.6.

2. Contact algorithm, material properties and failure criteria

2.1. Anisotropic contact algorithm

The numerical contact algorithm is based on the influence matrix theory [7]. The elements of the influence matrix are obtained by FE modelling of a segment of the anisotropic 'half-space'.

2.1.1. Elastic case

To solve the contact problem, first the examined contact area should be discretized according to Fig. 2. The analysed contact area is divided into $(N - 1) \times (M - 1)$ rectangles with sizes of $2.4 \times 2B$. The contact parameters will be assigned to the corner points of the rectangles. They are denoted by row and column indices. The contact pressure distribution is divided into pressure segments acting over the small rectangles located around the corner points. As two examples, a unit pressure is applied at point $k_l$ and a contact area, $A_3$, is composed by using five pressure segments (the $z$ axis represents the direction and magnitude of the contact pressure).

To start with, both rough surfaces should be discretized and brought into a single point initial contact. The initial gaps $h_{ij}$ can be assigned to each pair, while $u_{ij}^{(1)}$ and $u_{ij}^{(2)}$ are the elastic displacements of body 1 and body 2 due to the contact pressure distribution. The sum of the initial gaps of both bodies is $h_{ij}$ relative to the single point contact.

According to the geometric conditions of contact, the sum of the initial gap and the elastic displacements at the points of the real contact area $A_i$ are equal to the normal (distance) approach, $\delta$ (in the following equations, $\delta_{ij}$ is assigned to the discretized points), while outside $A_i$ they are greater:

$$\delta_{ij} = h_{ij} + (u_{ij}^{(1)} + u_{ij}^{(2)}) \quad \text{(over the contact area)}$$

$$\begin{align*}
\delta_{ij} &< h_{ij} + (u_{ij}^{(1)} + u_{ij}^{(2)}) \quad \text{(outside the contact area)} \\
p_{ij} &> 0 \quad \text{(over the contact area)} \\
p_{ij} &\equiv 0 \quad \text{(outside the contact area)}
\end{align*}$$

The stress conditions of contact express the fact that the acting pressures inside the contact area are greater than zero; at the same time, no pressure exists outside and along the borders of the contact area:

$$p_{ij} > 0 \quad \text{(over the contact area)}$$

$$p_{ij} \equiv 0 \quad \text{(outside the contact area)}$$

To fulfil these conditions, the contact pressure distribution, i.e., its location and magnitude, should be evaluated for a given normal approach and an initial gap field.

The relationship between the pressure and elastic displacement can be formed in the following way. The displacement of point $i, j$ of body 1 due to the unit pressure acting around point $k_l$ is $w_{ijkl}^{(1)}$ (Fig. 2). The total displacement of point $i, j$ due to the continuously acting pressure segments is then

$$u_{ij}^{(1)} = \sum_{k=1}^{N} \sum_{l=1}^{M} w_{ijkl}^{(1)} p_{kl} \quad (i = 1, \ldots, N) \quad (j = 1, \ldots, M)$$

A similar equation may be formed for body 2. Substituting these two equations into Equation 1a leads to

$$\delta_{ij} = h_{ij} + \sum_{k=1}^{N} \sum_{l=1}^{M} w_{ijkl} p_{kl} \quad (i = 1, \ldots, N) \quad (j = 1, \ldots, M)$$

where

$$w_{ijkl} = w_{ijkl}^{(1)} + w_{ijkl}^{(2)}$$