Finite Element Studies into Incomplete Coverage in Shot-Peening

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ABSTRACT

The present study examines two aspects of the co-indentation process; in particular it was desired to investigate: (i) the influence of punch separation upon the resulting residual stress field, and (ii) the successive development of and interaction between the plastic zones for different incremental indentation pressures.

The results of the work were then extended to take into account the importance of separation between punches to incomplete coverage in the shot-peening process. In particular, the work attempts to examine the critical separation beyond which the relevant residual stresses change from compression to tensile. The present work highlights the fact that compressive residual stresses resulting from incomplete coverage were attained even for a large separation ratio (e.g., c/a = 4).

KEYWORDS

Co-indentation; fatigue; finite-element; incomplete-coverage; plastic-zone; residual stresses, shot-peening.

1. INTRODUCTION

Suppose in a peening process a target surface area A is exposed to the jet stream. Let the projected area produced by plastic indentation due to each shot striking the surface be b. Thus, even if the number of shots impinging on the target surface is (A/b), the whole of the target surface area would not necessarily be covered by indentations, some parts of the target would be struck by a shot more than once, and the others would escape. The ratio between the area covered by the plastic indentations S and the total surface area of the component A is the coverage C. Complete or full coverage means that S = A and C is therefore 100%.

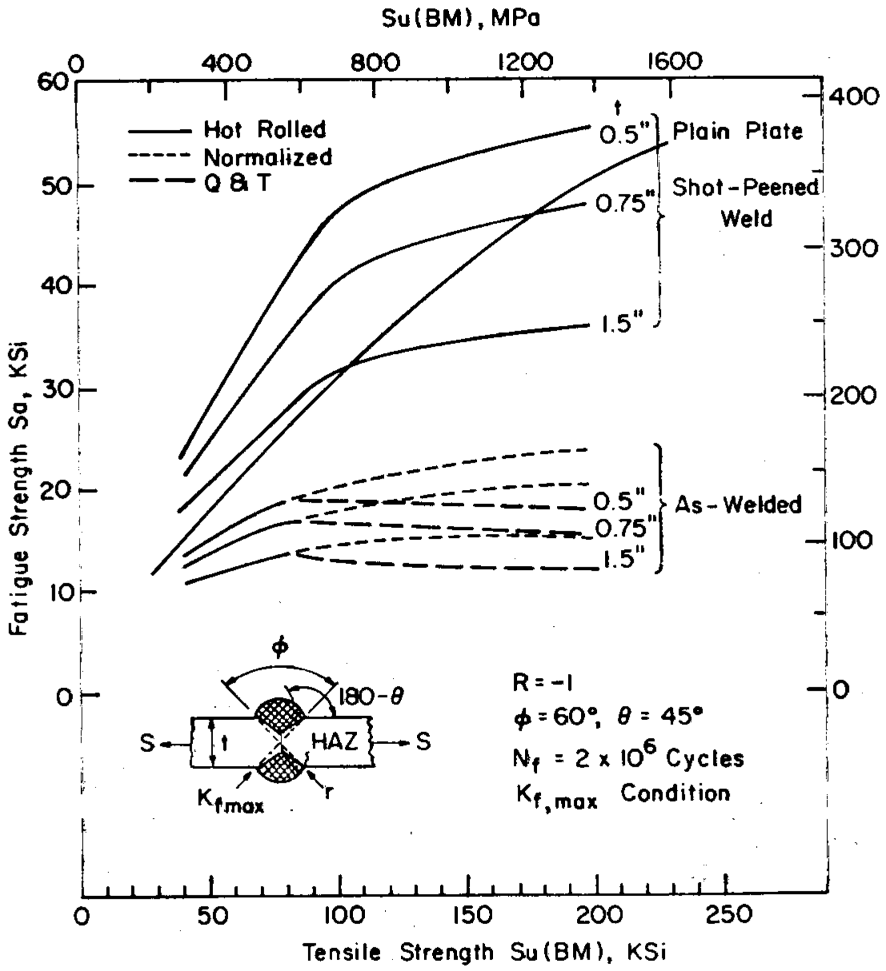

Fig. 8 Predicted Effect of Thickness (t) of Weldment on Fatigue Strength as Function of BM Tensile Strength for As-Welded and Shot-Peened Weldments (R = -1).

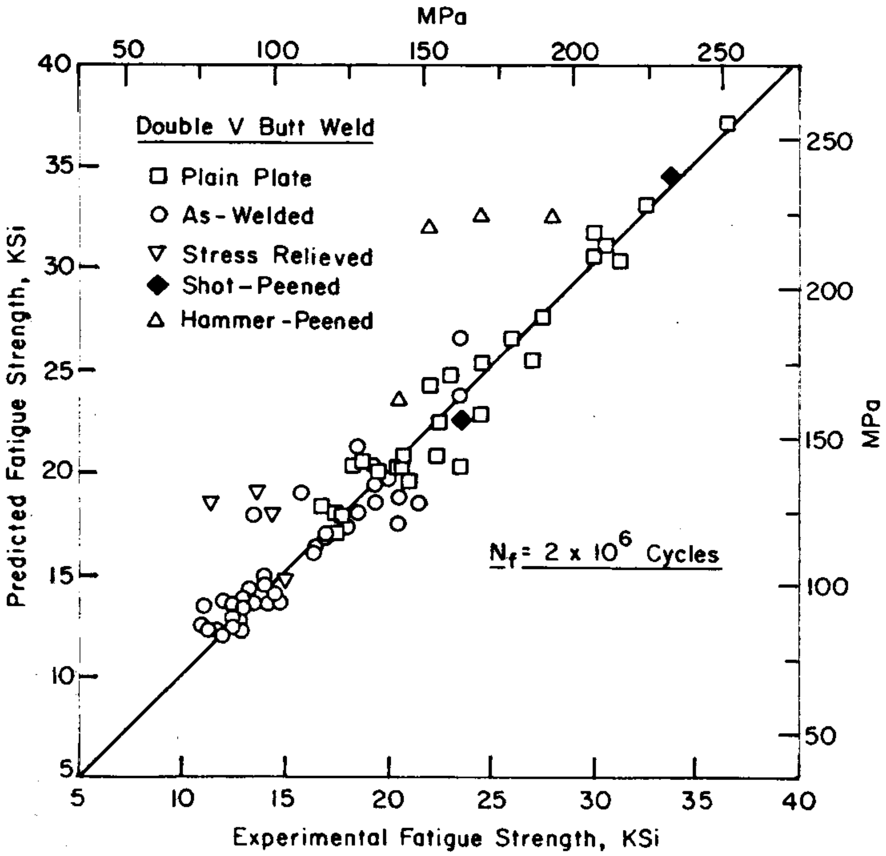

Fig. 9 Comparison of Predicted Fatigue Strength with Experimental Data from this Study and the University of Illinois Fatigue Data Bank (Radziminiski, 1973).

It is worth noting that in some circumstances, e.g., in the peening of very hard metals, and very complex geometries, it is difficult not only to achieve but also to monitor full coverage. The presence of un-peened areas in a peened component could represent a problem to the designer, especially if the implications of incomplete coverage are not well understood. Ultimately, it is the compressive residual stress field that controls the initiation and early stage propagation of fatigue damage. It is, therefore, of paramount importance to examine the effect of incomplete coverage upon the resulting residual stress field.

It is worth mentioning that problems concerned with the elasto-plastic indentation behaviour of metallic components have received considerable attention since the pioneering investigation of Prandtl 1920 (1). None of these investigations, except the work by Meguid (2) and Meguid et al (3), have dealt with the problem of co-indentation of a bounded solid by two flat plane rigid punches and its relevance to shot-peening. In their work, the co-indentation problem was investigated experimentally using etching techniques and theoretically using upper-bound solution, and no calculations were made of the unloading residual stresses, and for this reason the present investigation was undertaken.

The complete and accurate solution of incomplete coverage in shot-peening is very complex. However, in order to simplify the situation an elasto-plastic non-linear finite element analysis of the simultaneous indentations of a bounded solid of height h, width w and thickness t by two flat-plane rigid smooth punches under plane-strain conditions was considered. The punch width is assumed to be 2a and separation distance 2c; see Fig. 1 for details of nomenclature. The bounded solid is assumed to be made from an elastic linear strain-hardening material, which could be identified by the elastic modulus E, the plastic modulus E_p and the yield stress σ_y. The relevant properties of the model material (mild steel) used in this study are: Young's modulus $E = 209$ GN/m^2, Poisson's ratio $\nu = 0.3$ and yield stress $\sigma_y = 240$ MN/m^2. The analysis pertains to quasi-static indentations and strain-rate and inertia effects were ignored. It is also interesting to note that due to the symmetrical nature of the problem and consequently the solution, only one-half of the bounded solid was examined.

The present theoretical investigations were carried out by utilising the standard facility of 'PAFEC 75' suite of finite element programs detailed in Ref. (4). The current elasto-plastic solutions were obtained using incremental punch pressure and method of successive elastic solutions. The appropriate solution for a pre-determined increment of indentation pressure was obtained iteratively using a compromise method of solution between initial strain and initial stress approaches. For the solutions reported here, the accuracy criterion adopted was that the discrepancy resulting from successive estimates of the calculated equivalent stress at each gauss point should not exceed 1% of the provided equivalent stress (material property) at a given value of an equivalent plastic strain.

In the present study, particular attention was devoted to examining the effect of varying the interference ratio (c/a), the height (h) and the strain-hardening characteristics (H') of the bounded solid upon: (i) the resulting stress field at the centre-line of the bounded solid, and (ii) the successive development of plastic zone for different incremental indentation pressure. The results of the work were also extended to take into account the relevance of separation between punches to incomplete coverage in the shot-peening process.

2. ANALYSIS OF RESULTS AND DISCUSSIONS

The present investigation into the incomplete coverage of shot-peened components is simplified by co-indentation of a bounded solid by two flat-plane smooth rigid punches. In spite of the fact that in the present study no account was taken of the inertia, strain-rate and multiple indentation effects, the residual stress patterns illustrated in Figs. 2, 3 and 4 closely resemble those generated by shot-peening. This resemblance could be attributed to the hypothesis that the interaction between the plastic zones and recovery of both elastic and plastic regions is similar for both the static and dynamic problems. It is anticipated however, that the magnitudes of the resulting plastic zone and compressive residual stresses will be different.

It is interesting to note that when the indentation pressure is large enough, the region close to the punch deform plastically in tension and remaining remote area deform elastically. Upon unloading, the elastically stressed sub-layers tend to recover their original dimensions, but the continuity of the material in both regions, the elastic and plastic, does not allow this to occur. Consequently, a residual stress system will be trapped in the bounded solid. Because of the importance of the normal residual stresses σ^{r}_{xx} to the beneficial effects of shot-peening to component fatigue life, it was thought desirable to devote our attention to those stresses. It was also thought reasonable to concentrate upon the resulting residual stress field at the centre line of the bounded solid for c/a = 4, as this will highlight the effects of incomplete coverage in shot-peening.

2.1 *Effect of Interference Ratio, Height and Strain-Hardening upon Resulting Residual Stresses*

Fig. 2 illustrates the effect of the interference ratio (c/a) upon the resulting residual stress pattern at the centre-line of the bounded solid. It is interesting to note that the maximum residual stress occurs at a distinct distance below the surface. This figure also demonstrates that increasing the interference ratio (c/a) from 0 to 4 results in a decrease in the maximum compressive residual stress $\overset{*}{\sigma}{}^{r}_{xx}$ from 37.57 MN/m^2 to 14.85 MN/m^2 and a decrease in depth of the maximum compressive residual stress from 6.8 mm to 1.2 mm.

The study was extended to include the effect of varying the height h and strain-hardening characteristics of the bounded solid upon the resulting residual stresses for $c/a = 4$. It appears from Fig. 3 that the residual stress profile changes from compression near the surface to tensile near the middle and back again to compression at the bottom of the bounded solid for $h/a = 20$. For $h/a \leq 10$, the profile changes sign only once and remains unaltered. Fig. 4 demonstrates that an increase in the strain-hardening coefficient H' results in an increase in the magnitude of the maximum compressive residual stresses for the same indentation pressures. This is expected since the increased H' results in a decrease in the plastic zone developed by the indenters. It is also interesting to note that the maximum residual stress occurs quite close to the surface at the centre line of the bounded solid.

2.2 *Effect of Interference Ratio, Height and Strain-Hardening upon the Development of Plastic Zones*

The development of the plastic zone and the manner in which the zone spreads are important aspects of the finite element solution to the present problem. Figs 5(a), 5(b) and 5(c) show a sequential illustration of the effect of the interference ratio (c/a), normalised height (h/a) and strain-hardening coefficient (H') upon the growth of the plastic zone for different punch loads. These figures confirm that there exists interference between the plastic zones for $0 \leq c/a \leq 1$ for a maximum pressure of 680 MN/m^2 and strain hardening coefficient $H' \leq 0.1$. The figures also indicate that an increase in the strain hardening coefficient H' (>0.1) decreases the spread of the plastic zone, resulting in separate plastic zones for the punches for the same co-indentation conditions. Fig. 5(c) demonstrates the effect of height upon both the spread of the plastic zone to the foundation for $0 \leq h/a \leq 10$, and the interference between the punches for $c/a = 1$.

3. CONCLUSIONS

The main aim of the present investigation was to study the effect of large separation ratios upon the resulting residual stresses beneath the uncovered area. In particular, it was desired to examine whether for large separation ratios ($c/a = 4$), the residual stress pattern changes to tensile near the surface.

It is worth noting that for all the separation ratios considered in this study, the residual stresses near the surface at the centre line of the bounded solid were compressive. It must be appreciated, however, that the maximum separation ratio used in the present study ($c/a = 4$) is unrealistic in actual peening applications. However, it represents an extreme value in order to enable the authors to assess its effect upon the residual stress pattern.

It is clearly possible to strengthen the relevance of the present study to incomplete coverage in shot-peening, for example, by considering the inertia, friction, statistical nature, and strain rate effects. It is therefore reasonable to assume that the shot-peening results of the study must be viewed with some caution. It is also worth mentioning that the improvement in component fatigue life is controlled by the percentage coverage; full coverage is obviously recommended for best fatigue life improvement.

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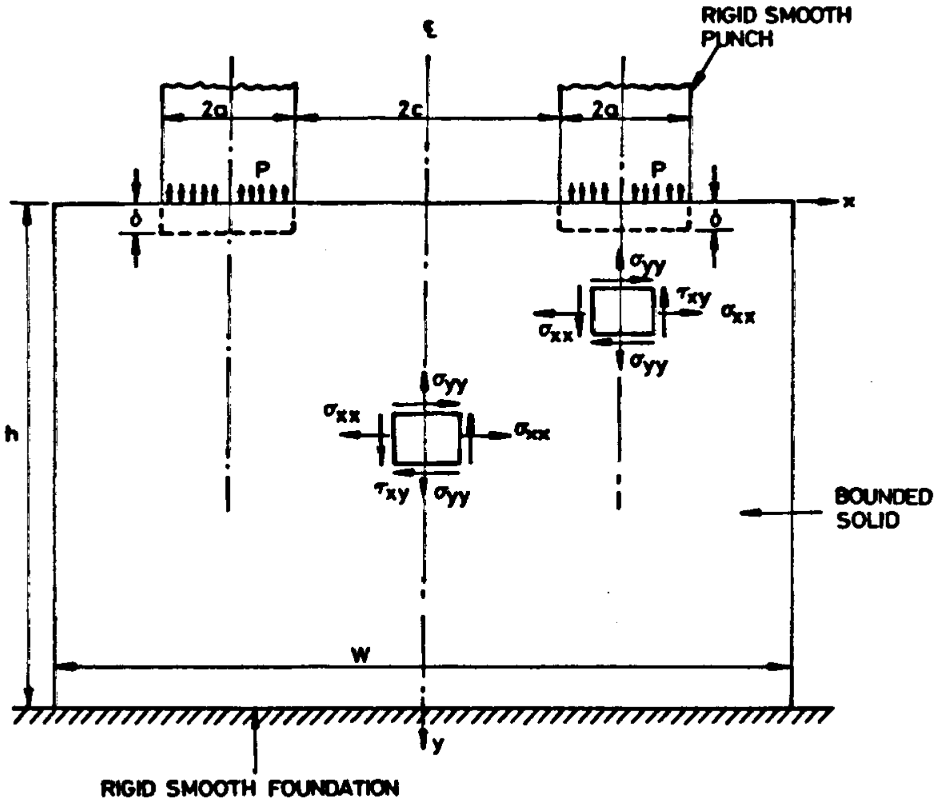

Fig. 1 A schematic showing notation used in the study

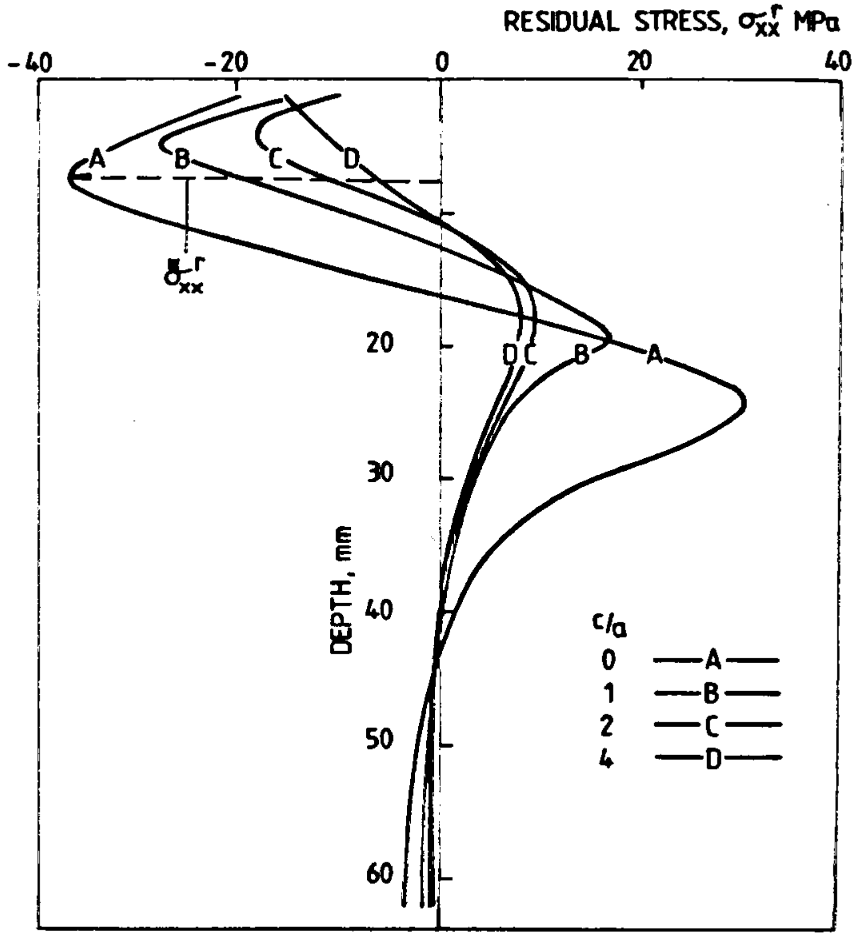

Fig. 2 Effect of interference ratio upon residual normal stress distributions (σ_{xx}^{r}) for H' = 0.2 and h/a = 20 at the centre line of the bounded solid

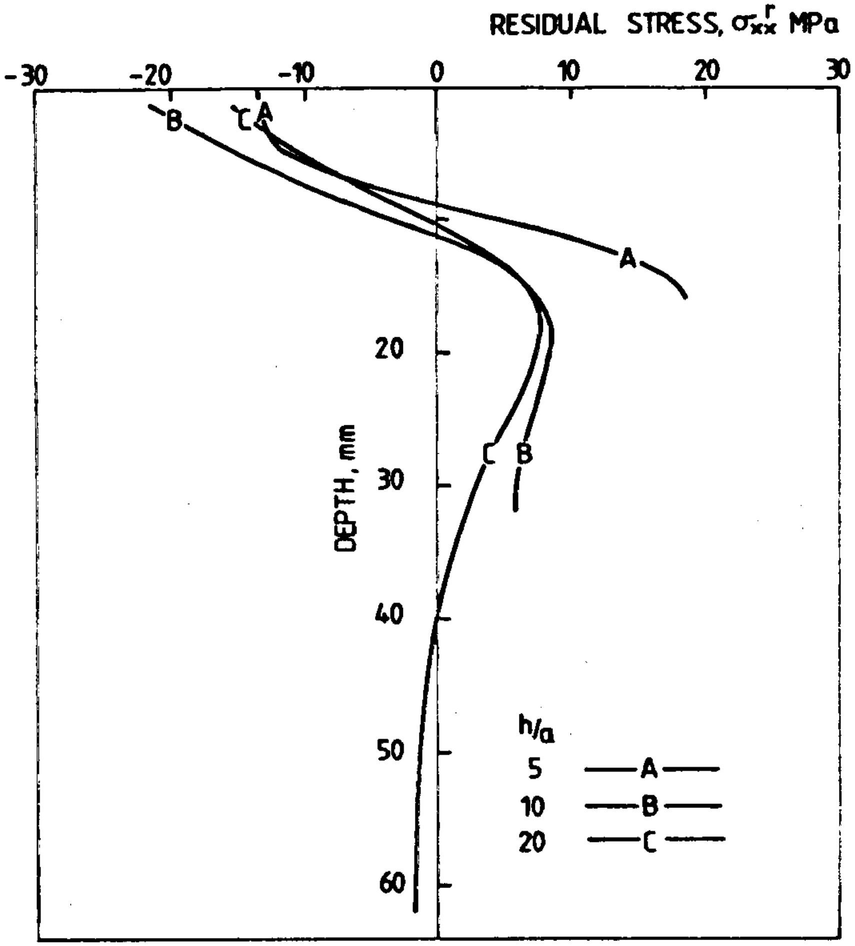

Fig. 3 Effect of height upon the residual normal stress distributions (σ_{xx}^r) for H' = 0.2 and c/a = 4 at the centre-line of the bounded solid

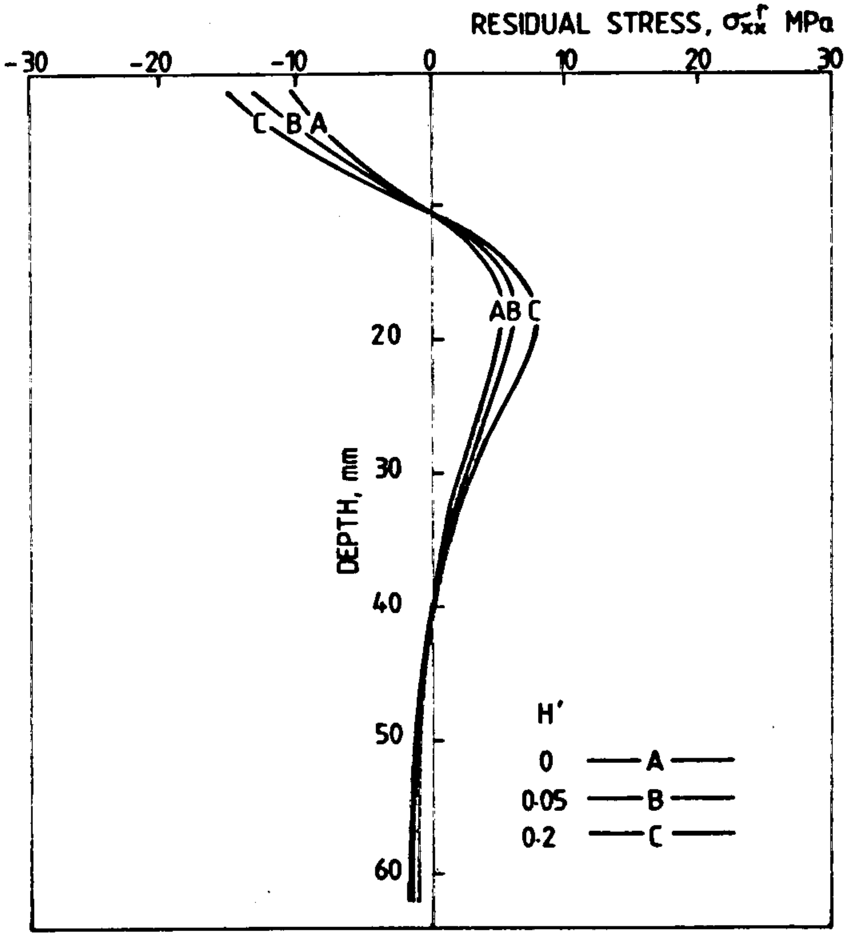

Fig. 4 Effect of strain-hardening upon residual normal stress distributions (σ_{xx}^r) for c/a = 4 and h/a = 20 at the centre line of the bounded solid

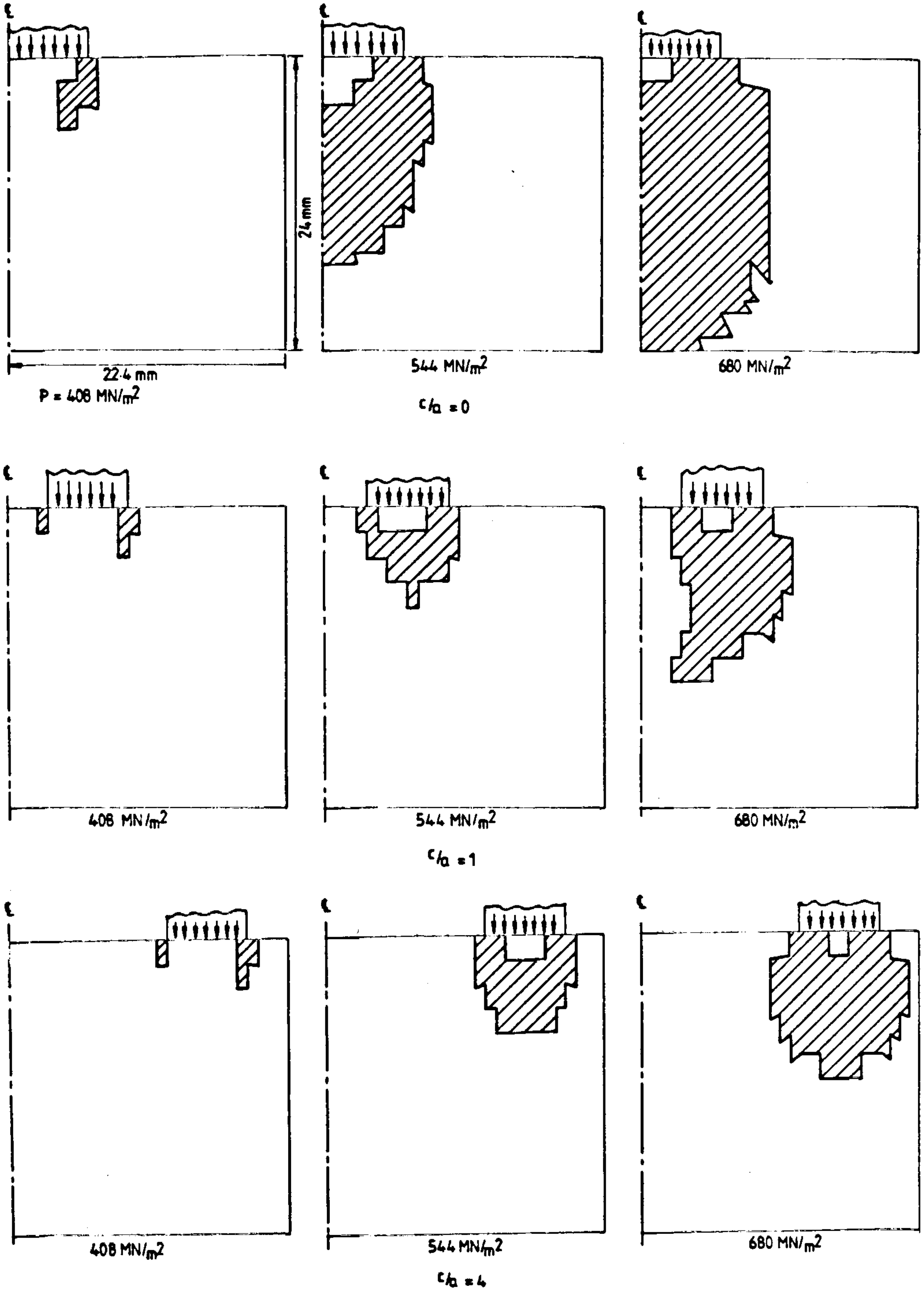

Fig. 5(a) Effect of interference ratio upon plastic-zone development for $H' = 0.2$ and $h/a = 20$

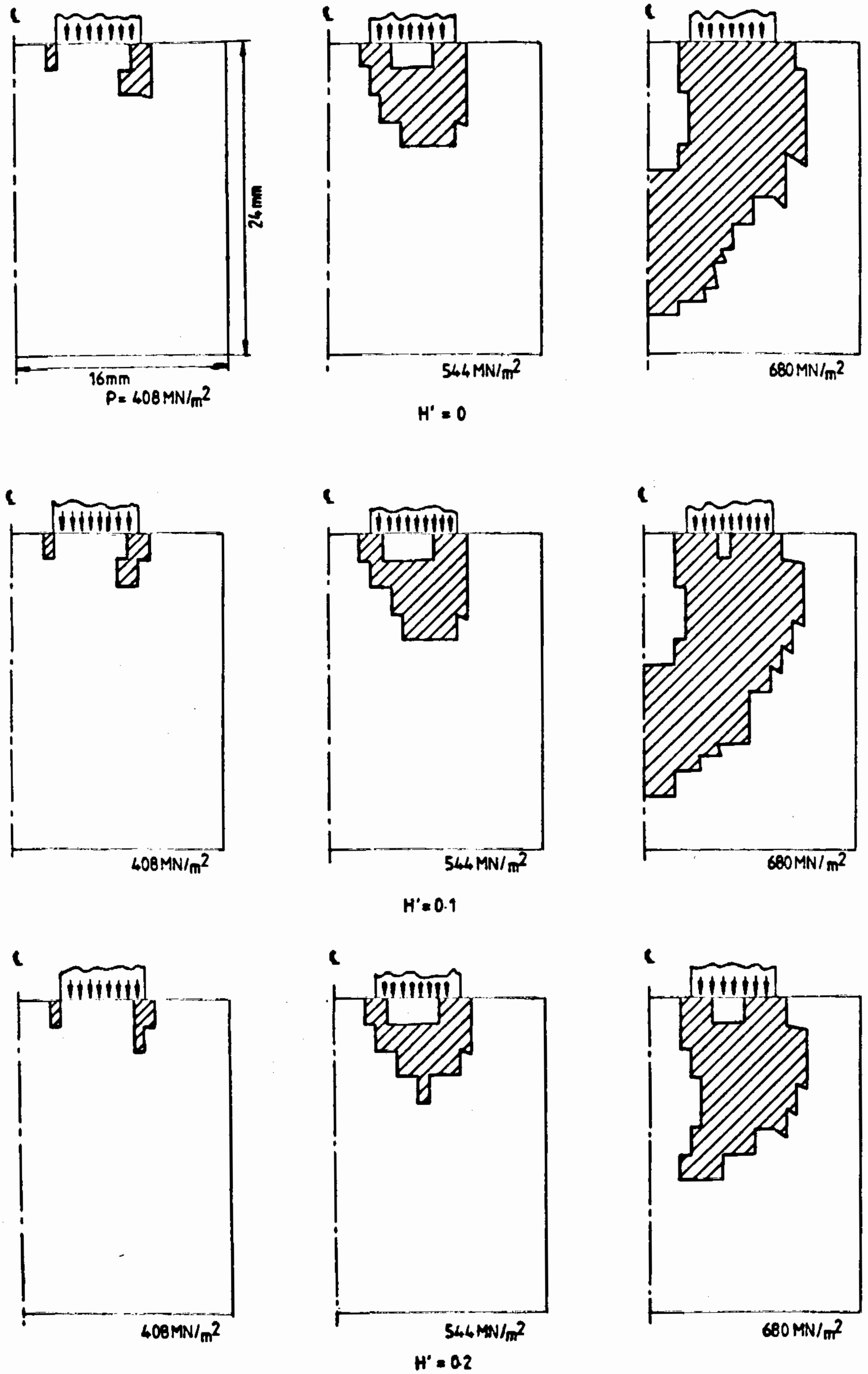

Fig. 5(b) Effect of strain-hardening upon plastic-zone development for $c/a = 1$ and $h/a = 20$

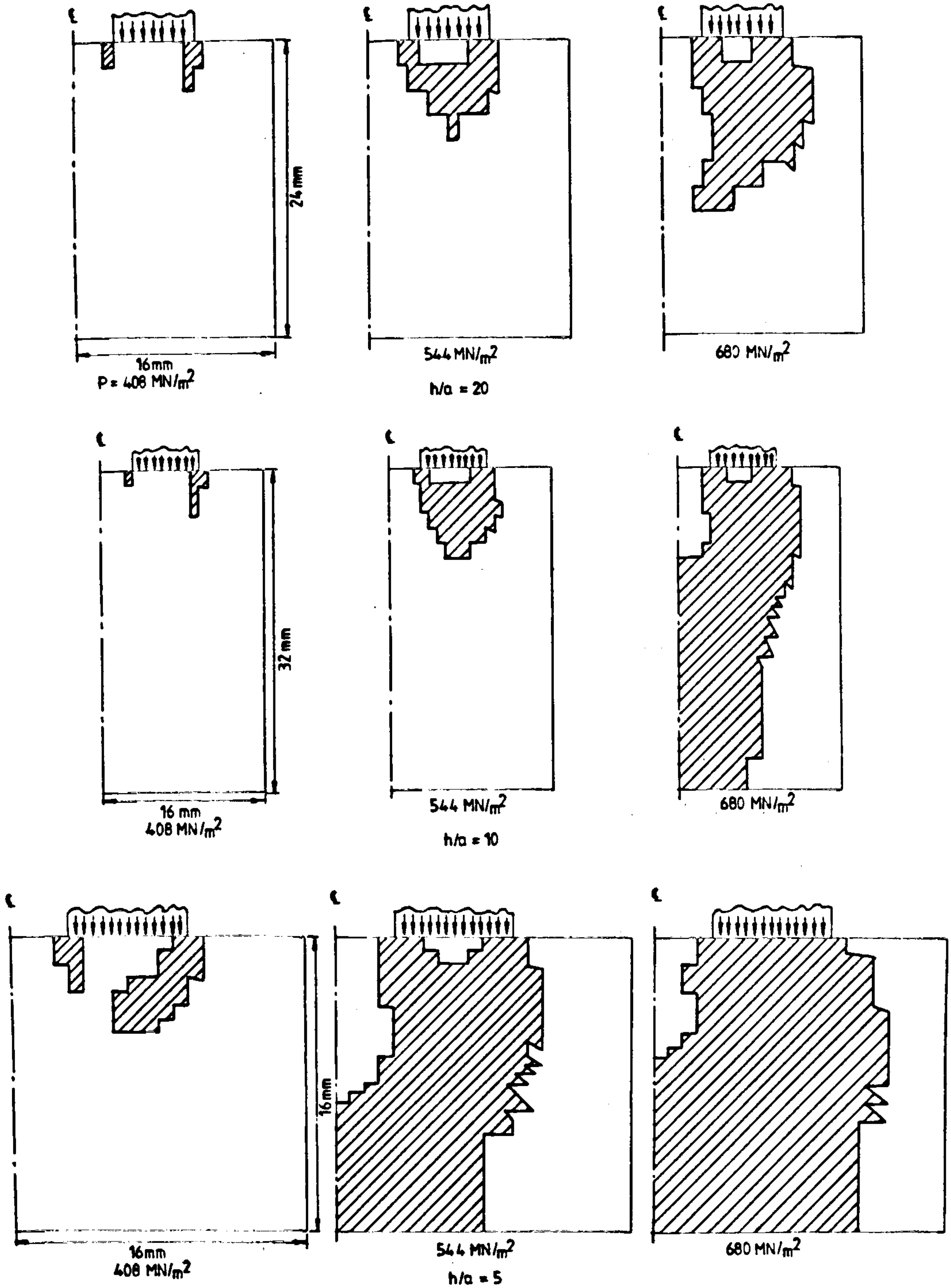

Fig. 5(c) Effect of height upon plastic-zone development for H' = 0.2 and c/a = 1