



## Benchmarking on bifurcation and localization in $J_2$ plasticity for plane stress and plane strain conditions

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### ABSTRACT

This paper studies the phenomenon of strain bifurcation and localization in  $J_2$  plasticity under plane stress and plane strain conditions. Necessary conditions for the outcome of bifurcation, localization, stress boundedness and decohesion are analytically established. It is shown that the explicit consideration of these conditions allows for the determination of localization angles in certain situations of interest that can be used to conduct benchmark tests on finite element formulations. The relative merits of irreducible, (stabilized) mixed and (displacement and/or strain) enhanced formulations are discussed. Numerical examples show that the mixed displacement/pressure formulation is to be preferred to the standard irreducible schemes in order to predict correct failure mechanisms with localized patterns of plastic deformation. Mixed elements are shown to be practically free from mesh directional bias dependence.

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### 1. Introduction

Structural collapse is often the consequence of the formation of strain localization bands whose width is very small compared to the length scale of the structure. Depending on the material, the phenomena behind the formation of these bands may be diverse: concentration of micro-structural defects, intergranular slip, crystal dislocation, etc. In granular materials, strains concentrate in shear bands whose width is at most one order of magnitude larger than the grain size. In metals, dislocations occur at an even smaller scale. Therefore, from the structural point of view the localization band is perceived as a fracture surface of negligible width. The amount of energy released during the formation of a fracture unit area is called fracture energy.

The question of modeling strain localization, formation of slip lines and subsequent structural collapse is a testing nonlinear problem in the field of computational mechanics. As with many other such challenges, solving real life, engineering problems can only be tackled by numerical procedures, such as the finite element method. Unfortunately, the results obtained in the initial attempts were bafflingly poor: either collapse mechanisms could not be numerically attained at all or if they could, they were strongly dependent on the mesh discretization used, both in terms of size and bias of the grid. In the last decades, many different finite element strategies have been tried on the issue, and the generated bibliography is voluminous.

The failure of the first attempts on the matter motivated studies directed to gain further insight in the subject of the necessary conditions for the occurrence of strain bifurcation and localization. The pioneering works by Hill [1,2] and Thomas [3] were taken up in more recent references [4–10]. The outcome of these efforts was that the necessary conditions for bifurcation and localization of elasto-plastic materials were identified and formulae were obtained for the orientation of the shear bands to be expected in general circumstances. However, lack of a convincing reason for the failure of finite element simulations to reproduce the analytical results persisted.

Most of the studies regarding localization with  $J_2$  plasticity have been carried out using the irreducible formulation, with the displacement field as the only primary variable. However,  $J_2$  plastic flow is isochoric by definition, and for strain localization to take place the plastic regime has to be well developed and, then, the (incompressible) plastic component of the deformation is dominant over the elastic part. Displacement-based finite element irreducible formulations are not well suited to cope with this quasi-incompressibility situation. The unsuitability of the irreducible formulation is more evident if low order finite elements are used which, conversely, are the first option when dealing with potentially discontinuous displacement and/or strain fields.

Reversely, the mixed displacement/pressure ( $\mathbf{u}/p$ ) formulation is a much more appropriate framework to tackle (quasi)-incompressible problems [13]. However, it is not straight-forward to construct stable mixed low order elements, and one of the successful lines of research that allows to achieve this is the use of stabilization methods. In previous works [14–20], the authors have used

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the orthogonal subgrid scale method to stabilize the mixed displacement–pressure method and applied it to the solution of incompressible elasto-plastic and damage problems. This stabilized framework leads to a discrete problem which is fully stable, free of pressure oscillations and volumetric locking and, thus, results obtained are not spuriously dependent on the directional bias of the finite element mesh.

The objectives of the present work are fourfold: (a) to revisit the analytical results on strain bifurcation and localization and to complement them with a requirement for stress boundedness and a decohesion condition that the localized solution must fulfill in the limit, (b) to clarify the specific difficulties encountered by low order finite element when dealing with strain localization problems and, particularly, with shear strain localization bands (c) to propose a series of benchmark problems in plane stress and plane strain situations for which the analytical solution is known and (d) to assess the relative performance of mixed and irreducible quadrilateral and triangular meshes in those benchmarks.

The outline of the paper is as follows. In Section 2, the mixed formulation for  $J_2$  plasticity is sketched. In Section 3, the necessary conditions for strain bifurcation and localization are revised; analytical solutions for the localization angle under plane stress and plane strain conditions are obtained from the stress boundedness requirement and the decohesion limit condition. In Section 4, the mechanical boundary value problem is stated in irreducible and (stabilized) mixed  $(\mathbf{u}/p)$  formulations. In Section 5, the approximability difficulties associated with strain localization problems are revised, discussing the role that displacement and/or strain enhancements may play. Section 6 presents results for a benchmark problem analyzed under plane stress and plane strain conditions with both irreducible and mixed elements. Finally, conclusions are drawn on the relative performance of the tested formulations.

## 2. $J_2$ plasticity constitutive model

For an elastoplastic model, the constitutive relation is expressed in total form as:

$$\boldsymbol{\sigma} = \mathbf{C} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) \quad (1)$$

where  $\boldsymbol{\sigma}$ ,  $\boldsymbol{\varepsilon}$  and  $\boldsymbol{\varepsilon}^p$  are the (second-order) stress, strain and plastic strain tensors, and  $\mathbf{C}$  is the (fourth-order) elastic tensor, which can be expressed as

$$\mathbf{C} = \left( K - \frac{2}{3}G \right) \mathbf{1} \otimes \mathbf{1} + 2G\mathbf{I} \quad (2)$$

where  $K$  is the bulk modulus,  $G$  is the shear modulus,  $\mathbf{1}$  is the second-order identity tensor and  $\mathbf{I}$  is the fourth-order symmetric identity tensor.

By definition, plastic flow in  $J_2$  plasticity is purely deviatoric. In such circumstances, it is advantageous to introduce the following split of the stress tensor  $\boldsymbol{\sigma}$  into its volumetric and deviatoric parts:

$$\boldsymbol{\sigma} = p\mathbf{1} + \mathbf{s} \quad (3)$$

where  $p = \frac{1}{3}\text{tr}\boldsymbol{\sigma}$  and  $\mathbf{s} = \text{dev}\boldsymbol{\sigma}$  are the pressure and the deviatoric stress, respectively.

The strain tensor  $\boldsymbol{\varepsilon} = \nabla^s \mathbf{u}$  ( $\mathbf{u}$  are the displacements) is split analogously:

$$\boldsymbol{\varepsilon}(\mathbf{u}) = \frac{1}{3}\varepsilon_v \mathbf{1} + \mathbf{e} \quad (4)$$

where  $\varepsilon_v = \text{tr}\boldsymbol{\varepsilon} = \nabla \cdot \mathbf{u}$  and  $\mathbf{e} = \text{dev}\boldsymbol{\varepsilon}$ , the volumetric and the deviatoric strain, respectively.

Correspondingly, the constitutive equation is split as:

$$p = K\varepsilon_v^e \quad (5a)$$

$$\mathbf{s} = 2G\text{dev}\boldsymbol{\varepsilon}^e = 2G\mathbf{e}^e \quad (5b)$$

where  $\varepsilon_v^e$  and  $\mathbf{e}^e = \mathbf{e} - \mathbf{e}^p$  are the elastic volumetric and the deviatoric parts of the strain tensor, respectively;  $\mathbf{e}^p$  is the (deviatoric) plastic strain tensor. In  $J_2$  plasticity, the volumetric part of plastic deformation is zero, so that  $\varepsilon_v = \varepsilon_v^e = \nabla \cdot \mathbf{u}$ .

Table 1 summarizes the  $J_2$  elasto-plastic model used in this work, accounting for isotropic softening. The *equivalent plastic strain* is defined as  $\xi = \sqrt{2/3} \int_0^t \|\dot{\mathbf{e}}^p\| dt$ , and the equivalent von Mises stress is  $\bar{\sigma} = \sqrt{3/2}\|\mathbf{s}\|$ .

The isotropic softening variable  $r = r(\xi)$  defines the current size of the yield surface  $\Phi(\mathbf{s}, r) = 0$ , as it controls the value of the radius of the von Mises cylinder (depicted in Fig. 1). Initially, when the equivalent plastic strain  $\xi = 0$ ,  $r$  is equal to the initial flow stress  $\sigma_0$ . Along the softening regime  $r$  diminishes and, for large value of the equivalent plastic strain, it eventually vanishes.

The plastic multiplier  $\dot{\gamma}$  is determined from the Kuhn–Tucker and consistency conditions. Details on how to efficiently integrate the  $J_2$  elasto-plastic constitutive model can be found in reference [13].

For the bifurcation and localization analysis in the next section, it is convenient to recall that Eq. (1) can also be expressed in rate form as:

$$\dot{\boldsymbol{\sigma}} = \mathbf{C}^{ep} : \dot{\boldsymbol{\varepsilon}} \quad (6)$$

where  $\dot{\boldsymbol{\sigma}}$  and  $\dot{\boldsymbol{\varepsilon}}$  are the (second-order) stress and strain rate tensors, and  $\mathbf{C}^{ep}$  is the (fourth-order) elasto-plastic tensor, which, for associative plasticity, can be expressed as [13]:

**Table 1**  
 $J_2$  plastic constitutive model.

- (1) Von Mises yield function,  $\Phi$ :  

$$\Phi(\mathbf{s}, r) = \|\mathbf{s}\| - \sqrt{\frac{2}{3}}r = \sqrt{\frac{2}{3}}(\bar{\sigma} - r)$$
- (2) Isotropic softening variable,  $r$ :  

$$r = \begin{cases} \sigma_0 \left( 1 - \frac{\eta_S}{\sigma_0} \xi \right) & 0 \leq \xi \leq \frac{\sigma_0}{\eta_S} \text{ linear softening} \\ 0 & \frac{\sigma_0}{\eta_S} \leq \xi \leq \infty \end{cases}$$

$$r = \sigma_0 \exp\left(-\frac{2\eta_S}{\sigma_0} \xi\right) \quad 0 \leq \xi \leq \infty \text{ exponential softening}$$

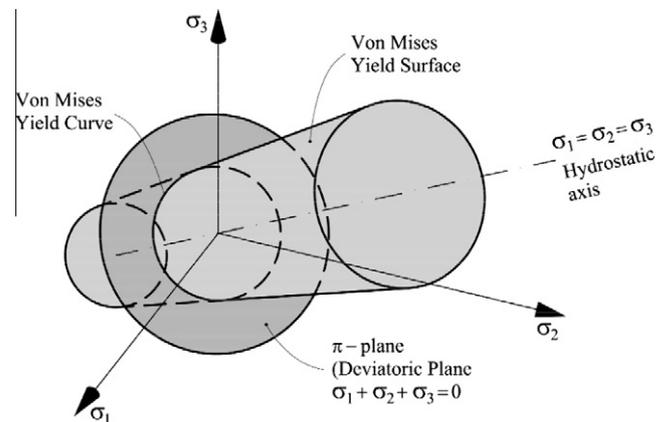
where  $\xi$  is the equivalent plastic strain,  $\sigma_0$  is the flow stress and  $\eta_S > 0$  is the softening parameter.
- (3) Plastic evolution laws:  

$$\dot{\mathbf{e}}^p = \dot{\gamma} \mathbf{m}$$

$$\dot{\xi} = \dot{\gamma} \sqrt{\frac{2}{3}}$$

where  $\dot{\gamma}$  is the plastic multiplier and the plastic flow tensor  

$$\mathbf{m} = \frac{\partial \Phi}{\partial \mathbf{s}} = \frac{\mathbf{s}}{\|\mathbf{s}\|}$$
 is normal to the yield surface.



**Fig. 1.** Yield surface for  $J_2$  plasticity in the stress space.

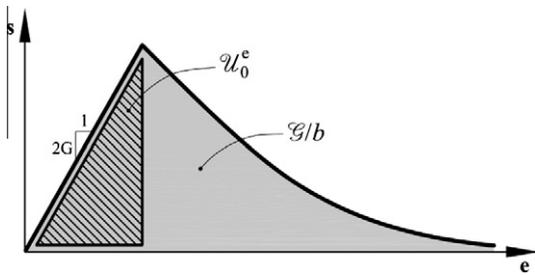


Fig. 2. Stress–strain curve with exponential softening.

$$\mathbf{C}^{ep} = \mathbf{C} - \frac{\mathbf{C} : \mathbf{m} \otimes \mathbf{m} : \mathbf{C}}{\mathbf{m} : \mathbf{C} : \mathbf{m} + \frac{2}{3}H} \quad (7)$$

where  $\mathbf{m} = \partial\Phi/\partial\mathbf{s}$  is the second-order plastic flow tensor and the hardening/softening modulus (in general, a function of  $\xi$ ) is  $H = H(\xi) = \partial r/\partial\xi$  (see Table 1).

With the definitions introduced above, the rate of deviatoric plastic work is  $\dot{\mathcal{W}}^p = \mathbf{s} : \dot{\mathbf{e}}^p = \bar{s}\dot{\xi} = r\dot{\xi}$ . Therefore, the total plastic work along a plastic process involving full softening, that is, from an elastic state  $t = 0$ ,  $\xi = 0$ ,  $r = \sigma_0$ , to a totally developed plastic state with  $t = \infty$ ,  $\xi = \infty$ ,  $r = 0$ , is equal to

$$\mathcal{W}_\infty^p = \int_{t=0}^{t=\infty} \dot{\mathcal{W}}^p dt = \int_0^\infty r(\xi) d\xi = \frac{\sigma_0^2}{2\mathcal{H}_S} \quad (8)$$

both for linear or exponential softening.

Being the elastic deviatoric strain energy at yielding  $\mathcal{U}_0^e = (J_2)_0/2G = (\sigma_0^2/3)/2G$  and defining the material brittleness number as  $\Pi_B = \mathcal{U}_0^e/\mathcal{W}_\infty^p$ , the softening parameter can be expressed as

$$\mathcal{H}_S = 2G\Pi_B \quad (9)$$

Let us now assume that plastic dissipation localizes in a band of width  $b$  (see discussion in the next section). Let us establish the requirements for this situation to be consistent with a limit case discrete model in which the strain energy is dissipated in a widthless discontinuity, say a slip line, and this dissipated energy per unit of slip line area is the fracture energy of the material  $\mathcal{G}$ .

The classical procedure [21–23], sketched in Fig. 2, is as follows. The total energy dissipated during the fracture process per unit volume  $\mathcal{D}$  within the localization band must fulfill the equation

$$\mathcal{D}b = \mathcal{G} \Rightarrow \mathcal{D} = \frac{\mathcal{G}}{b} \quad (10)$$

For a plastic model,  $\mathcal{D} = \mathcal{W}_\infty^p$ , and, using Eqs. (8) and (9), this renders:

$$\mathcal{H}_S = 2G\Pi_B = 2G \frac{\mathcal{U}_0^e}{\mathcal{G}/b} = 2G \frac{b}{\mathcal{L}} \quad (11)$$

where  $\mathcal{L} = (\mathcal{G}/\mathcal{U}_0^e)$  is the material length, which depends only on the material properties.

**Remark 1.** Eq. (11) makes the dimensional softening parameter  $\mathcal{H}_S$  dependent on the ratio  $b/\mathcal{L}$ . In turn, this makes the plastic multiplier  $\dot{\gamma}$  and the plastic strain rate *inversely* proportional to  $b/\mathcal{L}$ .

### 3. Bifurcation and localization analysis in J2 plasticity

#### 3.1. Continuous, localized and discrete failure. Failure analysis

Let us consider a solid domain  $\Omega$  subjected to a deformation evolution process leading to failure. Depending on the degree of

continuity of the displacement and strain fields leading to full material deterioration, failure can be classified as [9–12]:

- **Continuous failure:** when the kinematic compatibility conditions of a continuum medium are preserved during the deformation and fracture process, that is, displacement and strain fields are continuous, displacement and strain jumps do not appear,  $[[\dot{\mathbf{u}}]] = \mathbf{0}$ ,  $[[\dot{\boldsymbol{\varepsilon}}]] = \mathbf{0}$ .
- **Localized failure:** when continuous kinematic compatibility conditions are partially violated by the strain field during the failure process, that is, the displacement is continuous, but some strain components are discontinuous, strain jumps do appear,  $[[\dot{\mathbf{u}}]] = \mathbf{0}$ ,  $[[\dot{\boldsymbol{\varepsilon}}]] \neq \mathbf{0}$ .
- **Discrete failure:** when both the displacement and strain fields become discontinuous to produce a fracture, that is, displacement and strain jumps do appear,  $[[\dot{\mathbf{u}}]] \neq \mathbf{0}$ ,  $[[\dot{\boldsymbol{\varepsilon}}]] \neq \mathbf{0}$ .

For each type of failure to befall, there are necessary conditions that must be fulfilled. Analyzing the evolution of an increasing deformation process leading to failure (described by a stress–strain law such as the one depicted in Fig. 2 for a point undergoing failure), several conditions can be identified that act as failure diagnostics, in the sense that they mark the occurrence of necessary requisites for a certain type of failure to be initiated. These are: the bifurcation condition, the localization condition, the stress boundedness condition and the decohesion condition. In the following, these requirements are discussed.

For the sake of generality, hereafter we will consider a yield criterion of the form  $\Phi(\boldsymbol{\sigma}, r) = \bar{\sigma} - r = 0$ , where  $\bar{\sigma}$  is the equivalent stress and  $r = r(\bar{\varepsilon})$  is the isotropic softening variable;  $\bar{\varepsilon}$  is the equivalent strain. In J2 plasticity, the yield criterion is in fact independent of the pressure, so that  $\Phi(\mathbf{s}, r) = \bar{s} - r = 0$ , and the equivalent stress and strain are both purely deviatoric. Therefore, plasticity and failure are insensitive to the value of the mean stress. However, purely hydrostatic states are incompatible with plane stress conditions (because the out-of-plane normal stress is zero) or with plane strain conditions (unless the material is fully incompressible in the elastic range).

**Bifurcation condition.** This condition is usually associated to the stationarity of stress evolution with respect to the strain history,  $\dot{\boldsymbol{\sigma}} = \mathbf{0}$ . Because of the rate Eq. (6), the stationary condition, or limit state, implies

$$\det \mathbf{C}^{ep} = 0 \quad (12)$$

Because positive definiteness of the constitutive tensor is invoked to prove solvability and uniqueness of the irreducible mechanical problem in incremental form, Eq. (12) is often called the *loss of uniqueness* condition.

On one hand, loss of uniqueness is a necessary condition for *bifurcation* to take place, as it implies the existence of a limit or stationary stress point and two alternative possible solutions obtained by perturbing the stationary situation: one solution in which all material points proceed to deform forward (along a branch of the stress–strain curve with negative slope) and another solution in which some points deform forward and some others backward (unloading along the branch with positive slope). On the other hand, Eq. (12) is not sufficient for bifurcation as it would be met at an inflection point in the stress–strain relation if such point existed and that would *not* imply loss of uniqueness of the solution.

The necessary condition for (continuous or discontinuous) failure to materialize is that there exist strain rates  $\dot{\boldsymbol{\varepsilon}}$ , such that  $\dot{\boldsymbol{\sigma}} : \dot{\boldsymbol{\varepsilon}} \leq 0$  and, therefore:

$$\dot{\boldsymbol{\varepsilon}} : \mathbf{C}^{ep} : \dot{\boldsymbol{\varepsilon}} \leq 0 \quad (13)$$

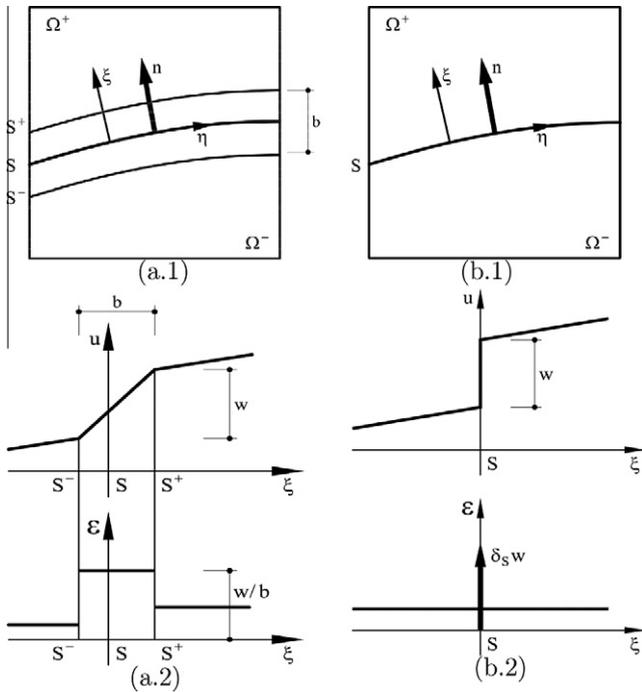


Fig. 3. Localized failure: (a) weak and (b) strong discontinuities.

Note that, for symmetric  $\mathbf{C}^{ep}$ , Eq. (12) is obtained by restricting Eq. (13) to the equality case.

**Localization condition.** This condition detects the possibility of formation of spatial discontinuities along material surfaces defined by a normal vector  $\mathbf{n}$ . The condition applies both to weak (strain) as to strong (strain and displacement) discontinuities depending on the severity of the jumps in the kinematic fields.

Consider the body  $\Omega$ , as shown in Fig. 3, crossed by a discontinuity  $S$ . Regions  $\Omega^+$  and  $\Omega^-$  are the parts of the body located “in front” and “behind”  $S$ . Consider, as in Fig. 3a.1, that  $S^+$  and  $S^-$  are two lines that run parallel to  $S$ , at a relative distance  $b$ . Surfaces  $S^+$  and  $S^-$  delimit a localization band of width  $b$  where strain localization may occur.

Let  $\mathbf{w} = \mathbf{u}^+ - \mathbf{u}^-$  be the difference between the displacement “in front” and “behind” the localization band and  $\boldsymbol{\beta} = \mathbf{w}/b$  be a deformation vector defined with respect to  $b$ . The top graph in Fig. 3a.2 shows a certain displacement component along a line normal to  $S$ , with the jump  $\mathbf{w}$  occurring continuously between  $S^-$  and  $S^+$ . The strain corresponding to the variation of the displacement along the line normal to  $S$  is shown in the bottom graph. The behavior inside the localization band is established through a softening stress–strain law like the one in Fig. 2.

Let us now consider the case of strong discontinuities. Note that such case can be formally constructed from the one previously discussed of a localization band of width  $b$  comprised between two weak discontinuities simply by taking the limit  $b \rightarrow 0$ . In this case, as shown in Fig. 3b.1, the weak discontinuities at lines  $S^+$  and  $S^-$  converge to a strong discontinuity at line  $S$ . Now,  $\mathbf{w} = \mathbf{u}^+ - \mathbf{u}^- = \llbracket \mathbf{u} \rrbracket$ , the difference between the displacement “in front” and “behind” the discontinuity line, is a real displacement jump; the deformation vector  $\boldsymbol{\beta} = \lim_{b \rightarrow 0} \mathbf{w}/b$  is not only discontinuous but unbounded (see Fig. 3b.2). The behavior of such a strong discontinuity must be established via a discrete softening traction–jump law or, through a *regularized* softening stress–strain law like in the previous case of a localization band [23].

Reversely, a localization band of width  $b$  bounded by two weak discontinuities can be viewed as a *regularized* strong discontinuity, and the corresponding softening stress–strain law as a regulariza-

tion of a certain discrete traction–displacement jump law. Hence, length  $b$  is not a physical length but a regularization parameter which can be made as small as desired. In FEM computations  $b$  is linked to the mesh resolution and the element size. This is the standpoint behind the softening regularization procedure described in Section 2 and the one that will be pursued throughout this work.

In localized failure, standard compatibility conditions of a continuum medium are replaced by Maxwell’s compatibility condition [3], which allows for jumps in the derivatives of the displacement field with respect to  $\xi$ , the direction normal to  $S$ , but not in the derivatives with respect to  $\eta$ , the direction tangential to  $S$  (see Fig. 3). According to Maxwell’s compatibility condition, the jump in the rate of the strain field between the inside and the outside of the localization band may be expressed exclusively in terms of the unit normal vector  $\mathbf{n}$  and the rate of the deformation vector  $\dot{\boldsymbol{\beta}}$  as  $\llbracket \dot{\boldsymbol{\epsilon}} \rrbracket = (\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s$ . According to Cauchy’s theorem, the jump on the variation of tractions,  $\dot{\mathbf{t}} = \mathbf{n} \cdot \dot{\boldsymbol{\sigma}}$  across the discontinuity lines  $S^+$  and  $S^-$  must be null,  $\llbracket \dot{\mathbf{t}} \rrbracket = \mathbf{0}$ . Assuming a linear comparison solid, this is shown to imply the singularity of the (second-order) acoustic tensor  $\mathbf{Q}^{ep} = \mathbf{n} \cdot \mathbf{C}^{ep} \cdot \mathbf{n}$ :

$$\det \mathbf{Q}^{ep} = 0 \quad (14)$$

The occurrence of this condition for a given pair  $\mathbf{n}$  and  $\mathbf{C}^{ep}$  implies the *loss of material ellipticity* of the constitutive relation and this is a necessary condition for the appearance of *weak discontinuities* and *localized failure* to take place. Eq. (14) is also called *discontinuous bifurcation condition*.

Classically, the problem of determining the onset of the discontinuous bifurcation consists in finding the first instant of the loading process (maximum value of the softening parameter  $H = H_{cr}$ ) and the corresponding orientation of the discontinuity  $\mathbf{n}_{cr}$  that satisfy that  $\det \mathbf{Q}^{ep}(H_{cr}, \mathbf{n}_{cr}) = 0$ .

Condition (14) is necessary but not sufficient for localization. Following reference [9], let us require that for the localization band to form and in subsequent instants, material points inside the band undergo plastic loading ( $\dot{\gamma} \geq 0$ ) while points outside the band unload elastically ( $\dot{\gamma} = 0$ ). If  $\dot{\boldsymbol{\epsilon}}_{reg}$  is the regular (unloading) strain rate which is common to the points outside and inside the localization band, the corresponding stress rates are:

$$\dot{\boldsymbol{\sigma}}_{ext} = \mathbf{C} : \dot{\boldsymbol{\epsilon}}_{ext} = \mathbf{C} : \dot{\boldsymbol{\epsilon}}_{reg} \quad (15a)$$

$$\dot{\boldsymbol{\sigma}}_{int} = \mathbf{C} : (\dot{\boldsymbol{\epsilon}}_{int} - \dot{\boldsymbol{\epsilon}}^p) = \mathbf{C} : (\dot{\boldsymbol{\epsilon}}_{reg} + (\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m}) \quad (15b)$$

where  $\llbracket \dot{\boldsymbol{\epsilon}} \rrbracket = \dot{\boldsymbol{\epsilon}}_{int} - \dot{\boldsymbol{\epsilon}}_{ext} = (\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s$  is the difference in the total strain rate, and the plastic strain rate is  $\dot{\boldsymbol{\epsilon}}^p = \dot{\gamma} \mathbf{m}$  ( $\dot{\gamma}$  is the plastic multiplier and  $\mathbf{m}$  is the plastic flow tensor). Therefore, the jump in the stress rate is:

$$\llbracket \dot{\boldsymbol{\sigma}} \rrbracket = \dot{\boldsymbol{\sigma}}_{int} - \dot{\boldsymbol{\sigma}}_{ext} = \mathbf{C} : [(\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m}] \quad (16)$$

Substituting, the traction equality,  $\llbracket \dot{\mathbf{t}} \rrbracket = \mathbf{n} \cdot \llbracket \dot{\boldsymbol{\sigma}} \rrbracket = \mathbf{0}$ , reads:

$$\mathbf{n} \cdot [\mathbf{C} : [(\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m}]] = \mathbf{0} \quad (17)$$

and this is an alternative stating of the discontinuous bifurcation condition in Eq. (14). Defining the elastic acoustic tensor as  $\mathbf{Q} = \mathbf{n} \cdot \mathbf{C} \cdot \mathbf{n}$  and making use of the symmetries of tensor  $\mathbf{C}$ , Eq. (17) determines uniquely the deformation vector rate  $\dot{\boldsymbol{\beta}}$  as:

$$\dot{\boldsymbol{\beta}} = \dot{\gamma} \mathbf{Q}^{-1} (\mathbf{m} : \mathbf{C} \cdot \mathbf{n}) \quad (18)$$

Let us now require, as said, that material points outside the band unload elastically, that is:

$$\mathbf{m} : \dot{\boldsymbol{\sigma}}_{ext} \leq 0 \quad (19)$$

while points inside the band comply with the consistency condition,  $\dot{\phi} = 0$ :

$$\dot{\Phi} = \frac{\partial \Phi}{\partial \boldsymbol{\sigma}} : \dot{\boldsymbol{\sigma}} + \frac{\partial \Phi}{\partial r} \dot{r} = \mathbf{m} : \dot{\boldsymbol{\sigma}}_{\text{int}} - \frac{2}{3} \dot{\gamma} H = 0 \quad (20a)$$

Using this result and Eqs. (16) and (19) can be rewritten as:

$$\frac{2}{3} \dot{\gamma} H \leq \mathbf{m} : \mathbf{C} : [(\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m}] \quad (21)$$

**Stress boundedness condition.** The stress tensor and its increments have to remain bounded during the failure process to keep their physical significance. Being  $\dot{\boldsymbol{\sigma}}_{\text{ext}}$  and  $\dot{\boldsymbol{\sigma}}_{\text{int}}$  both bounded, their difference,  $\llbracket \dot{\boldsymbol{\sigma}} \rrbracket$ , is bounded. From Eq. (16), it follows that the difference  $\llbracket (\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m} \rrbracket$  must be bounded. The deformation vector  $\dot{\boldsymbol{\beta}}$  is inversely proportional to the width of the localization band,  $b$ , and the plastic multiplier,  $\dot{\gamma}$ , must also be so (see Remark 1 in Section 2 and also Eq. (18)). As width  $b$  is a regularization parameter that can be made as small as desired, the stress boundedness condition requires that, for  $b \rightarrow 0$ , the two terms in the square brackets cancel out:

$$\llbracket \dot{\boldsymbol{\sigma}} \rrbracket = \mathbf{C} : [(\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m}] = \mathbf{0} \quad (22)$$

or, more explicitly:

$$\llbracket \dot{\boldsymbol{\epsilon}} \rrbracket = (\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s = \dot{\gamma} \mathbf{m} \quad (23)$$

The argument holds for a non vanishing width,  $b \rightarrow 0$ , with the additional stipulation that the stress and the stress rate tensors do not depend on such localization width, even if the deformation vector and the plastic multiplier do.

Note that Eq. (23) implies satisfaction of Eq. (21), as  $\dot{\gamma} \geq 0$  and in softening  $H \leq 0$ .

**Decohesion condition.** Let us consider a softening law designed to allow complete unloading outside the localization band and full decohesion across it at the end of the straining process (for equivalent strain  $\bar{\epsilon} \rightarrow \infty$ ). This law must be such that the softening parameter vanishes in the limit,  $\lim_{\bar{\epsilon} \rightarrow \infty} H = 0$ , as shown in Fig. 2. This means that the softening parameter  $H$  must increase during the final stages of the deformation process, from negative values to zero, asymptotically (like in exponential softening) or abruptly (like in linear softening).

For full unloading to be achieved outside the localization band at the end of the failure process, it must be

$$\lim_{\bar{\epsilon} \rightarrow \infty} \dot{\boldsymbol{\sigma}} = \mathbf{0} \quad (24)$$

As  $\dot{\mathbf{t}} = \mathbf{n} \cdot \dot{\boldsymbol{\sigma}}$ , this implies that there is complete decohesion (a null rate of traction) at the discontinuity (weak or strong) at the end of the straining process, that is

$$\lim_{\bar{\epsilon} \rightarrow \infty} \dot{\mathbf{t}} = \mathbf{0} \quad (25)$$

Starting from Eq. (24),  $\lim_{\bar{\epsilon} \rightarrow \infty} \dot{\boldsymbol{\sigma}}_{\text{ext}} = \mathbf{0}$  implies that the regular part of the strain rate must be zero,  $\lim_{\bar{\epsilon} \rightarrow \infty} \dot{\boldsymbol{\epsilon}}_{\text{reg}} = \mathbf{0}$ . In this situation, it must be  $\lim_{\bar{\epsilon} \rightarrow \infty} \dot{\boldsymbol{\sigma}}_{\text{int}} = \mathbf{C} : [(\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s - \dot{\gamma} \mathbf{m}] = \mathbf{0}$  and, therefore,

$$(\mathbf{n} \otimes \dot{\boldsymbol{\beta}})^s = \dot{\gamma} \mathbf{m} \quad (26)$$

Note that condition Eq. (26) is identical to Eq. (23). Hence, stress boundedness together with a softening law such that  $\lim_{\bar{\epsilon} \rightarrow \infty} H = 0$  implies that the decohesion condition is met in the limit.

**Remark 2.** Eq. (26) is different from Eq. (21), in the sense that it is more constrictive in the possibilities for the orientation  $\mathbf{n}$ . The fact that a given discontinuity orientation  $\mathbf{n}$  satisfies the localization condition  $\det \mathbf{Q}^{\text{ep}}(H, \mathbf{n}) = 0$ , for a given maximum (negative)  $H < 0$  value, does not guarantee stress boundedness, nor that the decohesion condition may be met in the limit

**Remark 3.** Reversely, the decohesion condition  $\dot{\boldsymbol{\sigma}} = \mathbf{0}$  (in the final stages of the deformation process) is identical to the bifurcation

condition  $\dot{\boldsymbol{\sigma}} = \mathbf{0}$  (necessary for the initiation of strain bifurcation), plus Maxwell's compatibility requirement for localization, plus the requirement of stress boundedness all along the localization process, *the decohesion limit included*. It follows that, after bifurcation occurs, Eq. (26) must hold all along the localization process.

**Remark 4.** Hence, Eq. (26) is the *necessary and sufficient* condition for the occurrence of bifurcation and localization of the strain field, with bounded stresses and decohesion in the limit case along a localization band (or a regularized strong discontinuity). This is why the term *strong discontinuity condition* was used in reference [10] for it. However, it applies to localization bands and strong discontinuities alike.

**Remark 5.** The physical interpretation of this condition is simple: all of the difference in the strain field between the interior and the exterior points of the localization band must be inelastic (plastic in this case).

**Remark 6.** For a given plastic flow tensor  $\mathbf{m}$  (and plastic multiplier  $\dot{\gamma}$ ), Eq. (26) may be used to determine the orientation of the discontinuity  $\mathbf{n}$  (and the rate of the deformation vector  $\dot{\boldsymbol{\beta}}$ ). As the corresponding equations are nonlinear, their solution is usually not unique or may not exist. This point is exploited in the next section.

**Remark 7.** The orientation of the discontinuity  $\mathbf{n}$  derived from Eq. (26) does not depend on the elastic properties. It depends only on the plastic yield surface adopted and the stress state.

### 3.2. Orientation of the discontinuity

The question of determining the orientation of the material surface exhibiting strain (in the weak discontinuity case) or displacement (in the strong discontinuity case) jumps has been object of some attention in the literature. Several authors [4–8] have found analytical and geometrical solutions for the *localization condition*, Eq. (21), using different strategies.

In this work, a different approach is adopted. Attention will be restricted to cases of  $J_2$  associative plasticity under plane stress and plane strain condition. In this cases, analytical expressions for the orientation of localization bands for which the *stress boundedness and decohesion condition*, Eq. (26), rather than the *localization condition*, Eq. (21), can be fulfilled are readily obtained. This procedure, used in references [9,10] for the analysis of strong discontinuities, is far more straight-forward than those used beforehand.

In the following, an orthonormal base  $\{\mathbf{n}, \mathbf{t}, \mathbf{p}\}$  is used, with  $\mathbf{n}$  normal to the surface  $S$ ,  $\mathbf{t}$  tangent to it and on the plane of interest

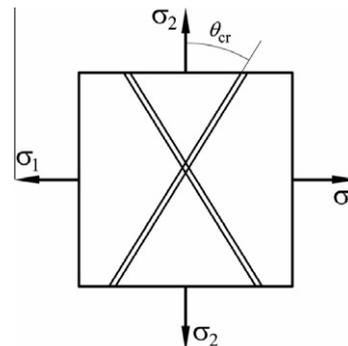


Fig. 4. Definition of critical localization angle.

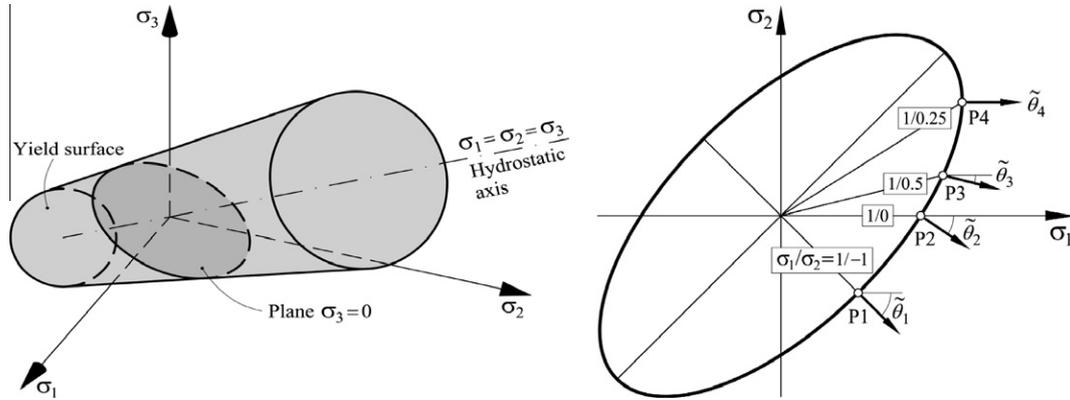


Fig. 5. Locus and flow directions and localization angles in plane stress conditions.

and  $\mathbf{p}$  orthogonal to the plane of the problem. In this base, the deformation vector rate can be expressed as  $\dot{\boldsymbol{\beta}} = \dot{\beta}_n \mathbf{n} + \dot{\beta}_t \mathbf{t}$ .

### 3.2.1. Plane stress conditions

In plane stress conditions, the out of plane components of the strain tensor need not be explicitly considered, since  $\sigma_3 = 0$  [13]. Then, Eq. (26) can be expressed in the base  $\{\mathbf{n}, \mathbf{t}, \mathbf{p}\}$  directly as

$$\begin{bmatrix} \dot{\beta}_n & \frac{1}{2}\dot{\beta}_t \\ \frac{1}{2}\dot{\beta}_t & 0 \end{bmatrix} = \dot{\gamma} \begin{bmatrix} m_{nn} & m_{nt} \\ m_{nt} & m_{tt} \end{bmatrix} \quad (27)$$

Therefore, the actual condition can be stated as:

$$m_{tt} = 0 \quad (28)$$

Let  $m_1, m_2 (m_1 > m_2)$  and  $\mathbf{e}_1, \mathbf{e}_2$  be the principal eigen values and the principal directions of the plastic flow tensor  $\mathbf{m}$ , respectively. Let  $\theta$  be the angle of  $\mathbf{n}$  with respect to  $\mathbf{e}_1$ , so that  $\mathbf{n} = \cos \theta \mathbf{e}_1 + \sin \theta \mathbf{e}_2$ . Then the component  $m_{tt}$  can be expressed as

$$m_{tt} = (m_1 - m_2) \sin^2 \theta + m_2 \quad (29)$$

From Eqs. (28) and (29) the critical angle (see Fig. 4 for its definition) can be computed as:

$$\sin^2 \theta_{cr} = -\frac{m_2}{m_1 - m_2} \quad (30)$$

Alternatively, Eq. (30) may be written as:

$$\tan^2 \theta_{cr} = -\frac{m_2}{m_1} = \tan^2 \tilde{\theta} \quad (31)$$

where  $\tilde{\theta}$  is the angle between the projection of the flow vector (normal to the yields surface cylinder) and the principal axis  $\sigma_1$  axis (see Fig. 5).

In the case of  $J_2$  plasticity, it is verified that  $m_i = s_i$ , where  $s_i$  are the deviatoric principal stresses.

Note that Eqs. (30) and (31) provide for two values for angle  $\theta_{cr}$  (see Fig. 4).

There are stress combinations for which  $\tan^2 \theta_{cr} < 0$ , and localization cannot occur. One example of this is equal bitension, with  $m_1 = m_2 > 0$ .

Using these results, Table 2 can be obtained for the critical orientations in different plane stress load combinations.

In a plane stress state, when yielding occurs, plastic flow determines if Eq. (28) is satisfied or not. If the corresponding Eq. (30) has solutions, these determine the direction of localization; if there are no solutions, localization cannot occur.

Fig. 5 shows that bifurcation of the strain field after yielding consists on the points inside the localization band undergoing further straining in the direction of the plastic flow (normal to the yield surface), while the points outside the localization band

Table 2

Localization angles for plane stress.

Stress components		Critical angle $\theta_{cr}$		
		$\sigma_1$	$\sigma_2$	
Plane stress	P1 Pure Shear	1.0	-1.0	45.00°
	P2 Uniaxial Tension	1.0	0.00	35.26°
	P3 Biaxial Tension 1	1.0	0.25	21.80°
	P4 Biaxial Tension 2	1.0	0.50	0.00°

Table 3

Localization angles for plane strain.

Stress components		Critical angle $\theta_{cr}$		
		$\sigma_1$	$\sigma_2$	
Plane strain	P1 Pure Shear	1.0	-1.0	45.0°
	P2 Uniaxial Tension	1.0	0.00	45.0°
	P3 Biaxial Tension 1	1.0	0.25	45.0°
	P4 Biaxial Tension 2	1.0	0.50	45.0°

unload elastically (to the origin). For the pure shear case, P1, bifurcation and localization befall without the need of strain rotation, because the direction of plastic flow coincides with the direction of elastic loading/unloading. However, for the other investigated stress combinations, P2 (uniaxial straining), P3 and P4 (mixed loading), a significant amount of reorientation of the principal strain directions takes place during the localization process. They have to rotate from being coaxial with the principal stress directions at the instant of yielding to be totally aligned with the plastic flow to be able to meet the decohesion condition.

### 3.2.2. Plane strain conditions

Under plane strain conditions, Eq. (26) in the base  $\{\mathbf{n}, \mathbf{t}, \mathbf{p}\}$  is

$$\begin{bmatrix} \dot{\beta}_n & \frac{1}{2}\dot{\beta}_t & 0 \\ \frac{1}{2}\dot{\beta}_t & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = \dot{\gamma} \begin{bmatrix} m_{nn} & m_{nt} & 0 \\ m_{nt} & m_{tt} & 0 \\ 0 & 0 & m_{pp} \end{bmatrix} \quad (32)$$

From this, it must be  $m_{tt} = 0$ , and then, as in plane stress, it follows that:

$$\tan^2 \theta_{cr} = -\frac{m_2}{m_1} \quad (33)$$

But, in this case, due to the plane strain constraint  $\epsilon_{pp} = 0$  and the flow rule  $\dot{\boldsymbol{\epsilon}}^p = \dot{\gamma} \mathbf{m}$ , the limit decohesion condition  $\dot{\boldsymbol{\sigma}} = \mathbf{0}$  implies  $\dot{\boldsymbol{\epsilon}} = \dot{\boldsymbol{\epsilon}}^p$  and:

$$m_{pp} = 0 \quad (34)$$

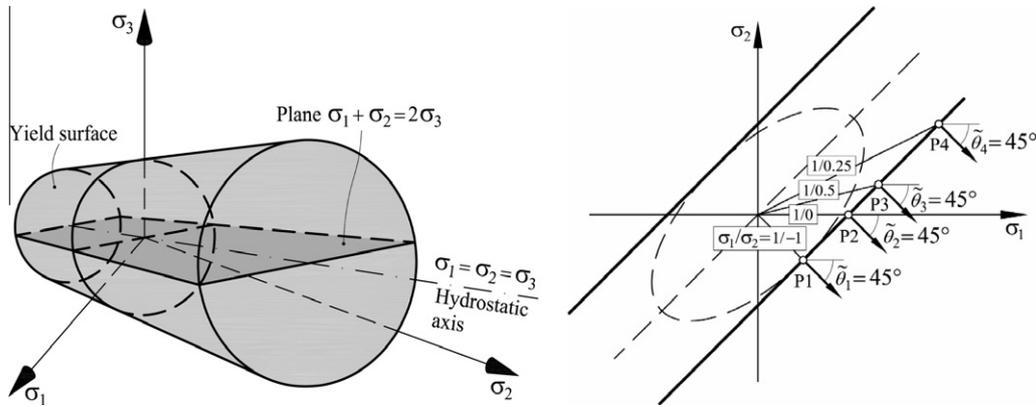


Fig. 6. Locus and flow directions and localization angles in plane strain conditions.

Taking into account that for a purely deviatoric flow  $m_{pp} = m_3 = s_3 = -(s_1 + s_2)$  and  $m_i = s_i$ , Eq. (34) implies that

$$s_3 = 0 \Rightarrow s_1 = -s_2 \Rightarrow m_1 = -m_2 \quad (35)$$

Replacing condition (35) into expression (33) it is concluded that the localization angle in plane strain condition is always  $\theta_{cr} = 45.0^\circ$ , irrespective of the stress loading conditions (see Table 3).

For a geometrical interpretation of the critical angle  $\theta_{cr}$ , consider that the condition  $s_3 = 0$  implies that the equality  $\sigma_1 + \sigma_2 = 2\sigma_3$  holds. This means that the necessary condition can only be met at the intersection of the yield cylinder and the plane  $\sigma_1 + \sigma_2 = 2\sigma_3$ , which is a plane that contains the hydrostatic axis  $\sigma_1 = \sigma_2 = \sigma_3$  and the line  $\sigma_1 + \sigma_2 = 0$  in the  $\sigma_3 = 0$  plane. This intersection is composed of two lines parallel to the hydrostatic axis, whose projections in the  $\sigma_1 - \sigma_2$  plane are two parallel lines at  $\tilde{\theta} = 45^\circ$  with the  $\sigma_1$  axis (see Fig. 6).

The intrinsic restriction  $\varepsilon_{pp} = 0$  that defines the plane strain condition deserves an additional comment. As explained above, condition  $m_{pp} = 0$  must be fulfilled all along the failure process; without it, bifurcation and localization cannot occur with bounded stress rates and the decohesion condition cannot be reached. This means that, unlike what happens under plane stress situations, bifurcation does not in general coincide with the onset of yielding. Substantial rotation of the principal strain directions has to take place from the onset of plastic behavior (where principal directions of strain and stress coincide and principal values are proportional), to the limit point where softening behavior may be initiated (where neither of the previous conditions happen). Only for pure shear, point **P1** in Fig. 6, it is  $\varepsilon_{tt} = \varepsilon_{pp} = 0$  in the elastic range, and thus yielding and bifurcation may happen at the same time (in fact, the pure shear case complies both with the plane stress and plane strain requirements). For the other investigated stress combinations, **P2** (uniaxial straining), **P3** and **P4** (mixed loading), stress will continue to rise under increasing strain after plastic flow. Only when a certain amount of plastic behavior has come about, with the corresponding reorientation of the principal strain directions, the localization process is set in motion. The more the stress state at yielding differs from pure shear, the larger this reorientation needs to be.

Note that the expression for the localization angle found both plane stress and strain conditions,  $\tan^2 \theta_{cr} = -(s_2/s_1)$ , does not depend on the elastic constitutive tensor  $\mathbf{C}$ : it is independent of the elastic material properties.

## 4. Irreducible, mixed and stabilized formulations

### 4.1. The irreducible formulation

The strong form of the irreducible  $\mathbf{u}$  formulation for the  $J_2$  plasticity continuum elasto-plasticity problem can be stated as: given

the elastic tensor  $\mathbf{C}$  and prescribed body forces  $\mathbf{f}$ , find the displacement  $\mathbf{u}$ , strain  $\boldsymbol{\varepsilon}$ , plastic strain  $\boldsymbol{\varepsilon}^p$  and stress  $\boldsymbol{\sigma}$ , fields, such that:

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{f} = \mathbf{0} \quad (36a)$$

$$\boldsymbol{\sigma} = \mathbf{C} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) \quad (36b)$$

$$\boldsymbol{\varepsilon} = \nabla^s \mathbf{u} \quad (36c)$$

The field of plastic strains,  $\boldsymbol{\varepsilon}^p$ , is computed locally in terms of the (deviatoric) stress field and its history.

These equations, subjected to appropriate Dirichlet and Neumann boundary conditions, must be satisfied in  $\Omega$ , the open and bounded domain of  $\mathbb{R}^{n_{\text{dim}}}$  occupied by the solid in a space of  $n_{\text{dim}}$  dimensions.

The strong form of the irreducible problem reduces to Eq. (36a), once Eqs. (36b) and (36c) are substituted. The corresponding discrete finite element form of the problem is obtained following the standard procedure:

$$(\nabla^s \mathbf{v}_h, \boldsymbol{\sigma}_h) - (\mathbf{v}_h, \mathbf{f}) - (\mathbf{v}_h, \bar{\mathbf{t}})_{\partial\Omega} = 0 \quad \forall \mathbf{v}_h \quad (37)$$

where  $\mathbf{u}_h, \mathbf{v}_h \in \mathcal{V}_h$  are the discrete displacement field and its variations, respectively, and  $(\cdot, \cdot)$  denotes the inner product in  $L^2(\Omega)$ .

### 4.2. The mixed $\mathbf{u}/p$ formulation

The strong form of the mixed  $\mathbf{u}/p$  formulation for the  $J_2$  plasticity continuum mechanical problem can be stated as: given the elastic properties ( $G, K$ ) and prescribed body forces  $\mathbf{f}$ , find the displacement  $\mathbf{u}$ , pressure  $p$ , deviatoric strain  $\mathbf{e}$ , deviatoric plastic strain  $\mathbf{e}^p$  and deviatoric stress  $\mathbf{s}$ , fields, such that:

$$\nabla \cdot \mathbf{s} + \nabla p + \mathbf{f} = \mathbf{0} \quad (38a)$$

$$\nabla \cdot \mathbf{u} - \frac{1}{K} p = 0 \quad (38b)$$

$$\mathbf{s} = 2G(\mathbf{e} - \mathbf{e}^p) \quad (38c)$$

$$\mathbf{e} = \text{dev}(\nabla^s \mathbf{u}) \quad (38d)$$

Substituting Eq. (38d) into Eq. (38c) and this into Eq. (38a), and following the standard procedure, the discrete finite element form of the problem is obtained:

$$(\nabla^s \mathbf{v}_h, \mathbf{s}_h) + (\nabla \cdot \mathbf{v}_h, p_h) - (\mathbf{v}_h, \mathbf{f}) - (\mathbf{v}_h, \bar{\mathbf{t}})_{\partial\Omega} = 0 \quad \forall \mathbf{v}_h \quad (39a)$$

$$(q_h, \nabla \cdot \mathbf{u}_h) - \left( q_h, \frac{1}{K} p_h \right) = 0 \quad \forall q_h \quad (39b)$$

where  $\mathbf{u}_h, \mathbf{v}_h \in \mathcal{V}_h$  and  $p_h, q_h \in \mathcal{Q}_h$  are the discrete displacement and pressure fields and their variations, respectively.

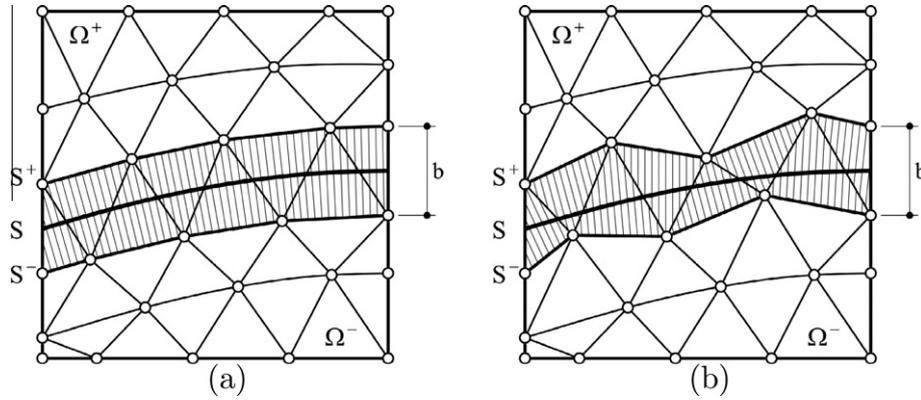


Fig. 7. Finite element simulation of localized failure: (a) well-aligned and (b) mis-aligned meshes.

#### 4.3. The stabilized mixed $\mathbf{u}/p$ formulation

In mixed formulations, selection of the interpolating finite element spaces is not a trivial question. Stability requirements pose severe restrictions on the choice of the spaces  $\mathcal{V}_h$  and  $\mathcal{Q}_h$  [24]. For instance, standard mixed elements with continuous equal order linear/linear interpolation for both fields are not stable, and the lack of stability shows as uncontrollable oscillations in the pressure field that usually, and very particularly in non linear problems, pollute the solution entirely. Fortunately, stabilization methods [25,26] can be developed to attain global stability with the desired choice of interpolation spaces. An appealing consistent stabilization method is the *orthogonal sub-grid scale method* [27,28], applied to the problem of incompressible elasto-plasticity, in small and finite strains, and continuum damage mechanics by the authors in previous works [14–20].

The basic idea of the orthogonal sub-grid scale approach is to consider that the continuous displacement field can be split in two components, one coarse and a finer one, corresponding to different scales or levels of resolution. Therefore, the displacement field is approximated as

$$\mathbf{u} = \mathbf{u}_h + \tilde{\mathbf{u}} \quad (40)$$

where  $\mathbf{u}_h \in \mathcal{V}_h$  is the displacement component of the (coarse) finite element scale and  $\tilde{\mathbf{u}} \in \mathcal{V}_h^+$  is the enhancement of the displacement field corresponding to the (finer) sub-grid scale, located in the space orthogonal to the finite element space.

In order to ensure *consistency* of the stabilized mixed formulation, that is, that the stabilized discrete solution converges to the continuous solution on mesh refinement, the sub-scale displacements are approximated in terms of the residual of Eq. (39a),  $\mathbf{r}_h = \mathbf{r}_h(\mathbf{u}_h, p_h) = \nabla \cdot \mathbf{s}_h + \nabla p_h + \mathbf{f}$ , as:

$$\tilde{\mathbf{u}} = \tau_e P_h^{\perp}(\mathbf{r}_h) = \tau_e (\mathbf{r}_h - P_h(\mathbf{r}_h)) \in \mathcal{V}_h^+ \quad (41)$$

where  $P_h$  is the  $L_2$ -projection (least square fitting) onto  $\mathcal{V}_h$  and  $P_h^{\perp} = I - P_h$  is the corresponding orthogonal projection onto  $\mathcal{V}_h^{\perp}$ . The stabilization parameter  $\tau_e = ch_e^2/2G_e^*$  is defined as a function of the characteristic length of the element  $h_e$  and the current secant shear modulus  $2G_e^* = \|\mathbf{s}_h\|/\|\mathbf{e}_h\|$ ;  $c$  is a constant  $c = \mathcal{O}(1)$ .

Using this enhancement for the approximation of the displacement field  $\mathbf{u}$ , the resulting *stabilized* mixed system of equations, for linear/linear displacement and pressure interpolations, is:

$$(\nabla^s \mathbf{v}_h, \mathbf{s}_h) + (\nabla \cdot \mathbf{v}_h, p_h) - (\mathbf{v}_h, \mathbf{f}) - (\mathbf{v}_h, \bar{\mathbf{t}})_{\partial\Omega_t} = 0 \quad \forall \mathbf{v}_h \quad (42a)$$

$$(q_h, \nabla \cdot \mathbf{u}_h) - \left( q_h, \frac{1}{K} p_h \right) - (\nabla q_h, \tau_e [\nabla p_h - \Pi_h]) = 0 \quad \forall q_h \quad (42b)$$

The nodal variable  $\Pi_h$  is the  $L_2$ -projection of the pressure gradient,  $\Pi_h = P_h(\nabla p_h)$ .

#### 5. Approximability of localized solutions in irreducible, mixed and enhanced formulations

In this Section we address the feasibility of modeling localized solutions using finite element formulations. In particular, we will consider the ability of irreducible and mixed formulations to reproduce in an adequate manner localization bands that aim to represent a regularized strong discontinuity and the necessity to enhance these formulations.

The very limited ability of standard finite elements to reproduce separation modes in general circumstances is well known. Consider, for instance, a mesh of linear P1 constant strain triangles, such as the one in Fig. 7, subjected to a separation motion in which the nodes located in the  $\Omega^+$  part of the domain have a relative displacement of  $\mathbf{w}$  with respect the  $\Omega^-$  part of the domain. Consider also, as in Fig. 3a, that  $S^+$  and  $S^-$  are two lines that run parallel to  $S$  (with normal  $\mathbf{n}$ ), at a relative distance  $b = h$ , this being the typical height of the triangular elements. Surfaces  $S^+$  and  $S^-$  delimit a localization band of width  $b$  inside which strain localization may occur. In this case,  $\mathbf{w} = \mathbf{u}^+ - \mathbf{u}^-$  is the difference between the displacements at  $S^+$  and  $S^-$  and  $\boldsymbol{\beta} = \partial \mathbf{w} / \partial \xi$  is a deformation vector defined by differentiation with respect to the normal coordinate  $\xi$ .

With linear elements, the deformation vector  $\boldsymbol{\beta}$  can only be approximated satisfactorily as  $\boldsymbol{\beta} = \mathbf{w}/h$ . This will, in fact, be the result obtained by projecting the exact separation mode on the finite

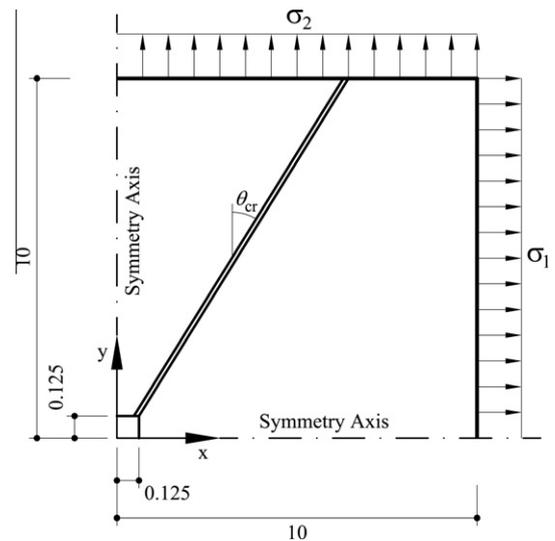


Fig. 8. Geometry and dimensions for benchmark problems.

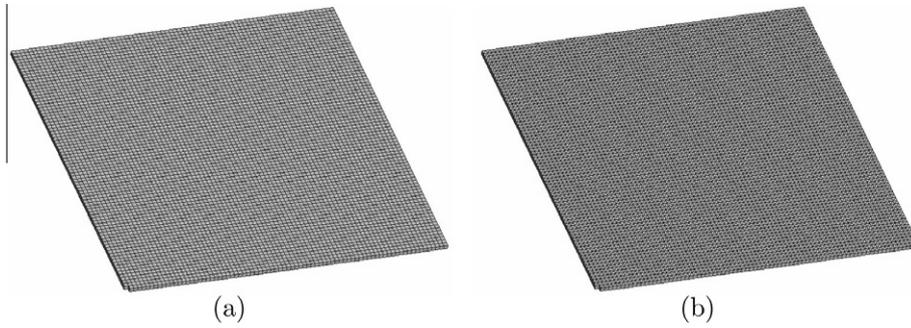


Fig. 9. (a) Q1Q1 and (b) P1P1 FE meshes used for benchmark problem.

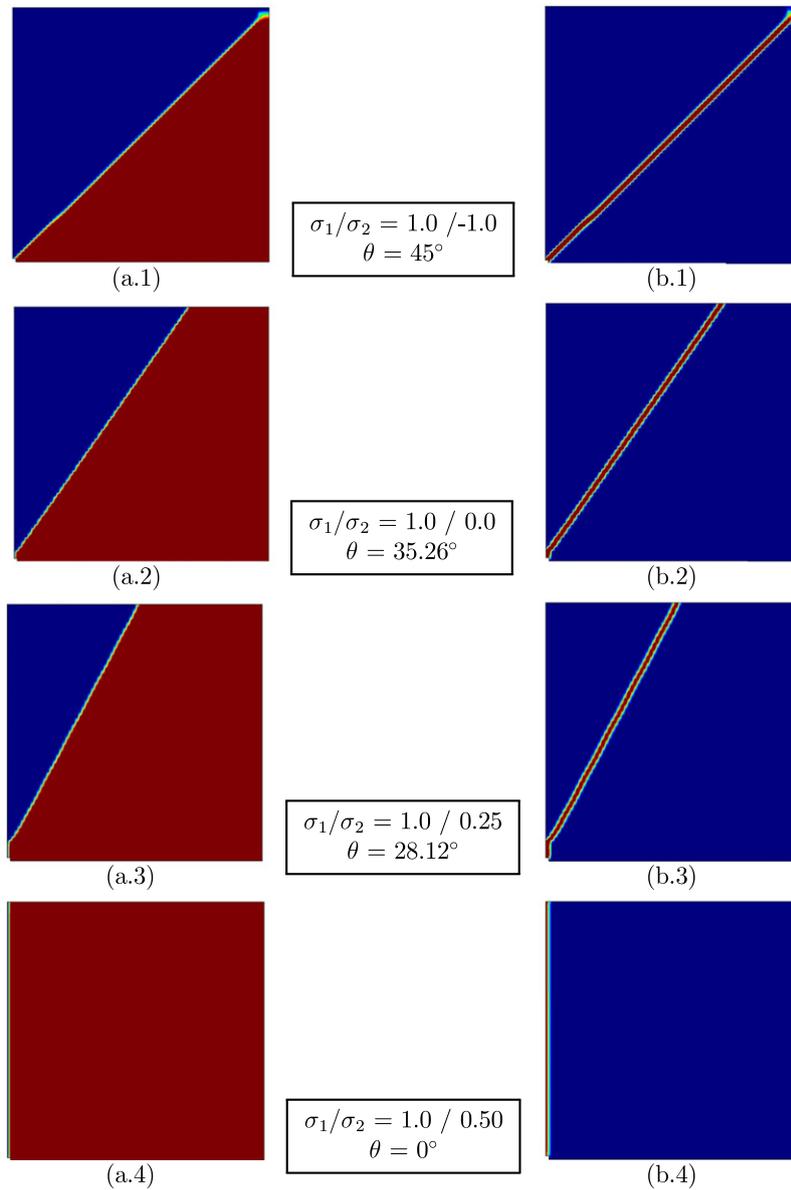
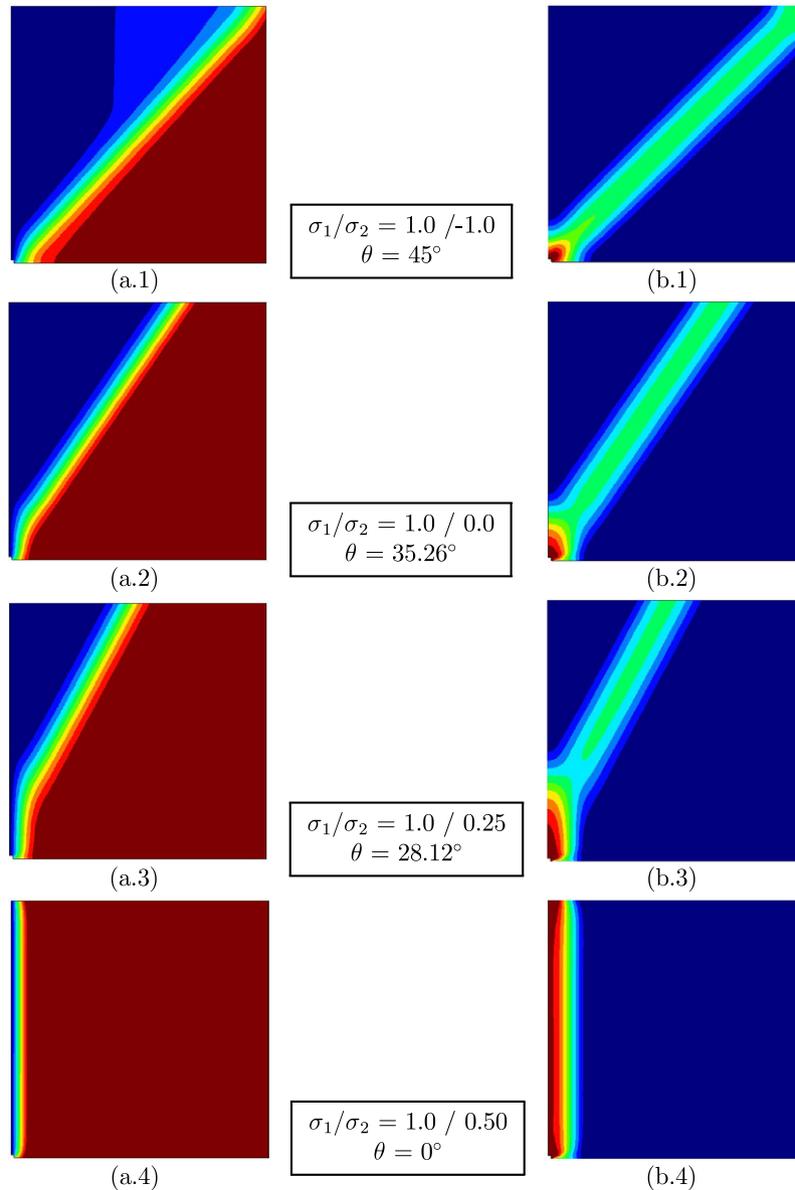


Fig. 10. Results for plane stress conditions with Q1Q1 mixed quadrilateral prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

element mesh of Fig. 3a. However, projecting the exact separation mode onto the finite element mesh of Fig. 3b, in which lines of nodes  $S^+$  and  $S^-$  are not parallel to the intended discontinuity line, will not yield the same (correct) results. This is because P1 ele-

ments can only reproduce a constant deformation mode of the form required by Maxwell's compatibility condition  $\dot{\epsilon} = (\mathbf{n} \otimes \dot{\beta})^s$  if  $\mathbf{n}$  is parallel to one of the sides of the triangles. The bilinear quadrilateral element Q1 shows similar shortcomings.



**Fig. 11.** Results for **plane stress** conditions with **Q1** irreducible quadrilateral prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

In particular, if we consider the problem of representing a slip separation mode, with  $\mathbf{w}$  normal to  $\mathbf{n}$ , an incorrect representation of shear deformation results in volumetric locking. Mixed  $P1P1$  or  $Q1Q1$  elements display a slightly better behavior than their corresponding irreducible counterparts, because incorporating an independent linear (or bilinear) interpolation of the pressure alleviates this fact. However, they share with the irreducible elements the same inherent problem with the deviatoric strain components.

The reason for this is that discrete solution spaces built from piecewise continuous polynomials cannot represent displacement discontinuities with arbitrary orientations inside the element, not even in a regularized fashion. This is purely an *approximability* shortage of the discrete solution spaces used for interpolating the displacement field, which are the same in the irreducible and mixed elements. However, the discomfitting approximability error is not eliminated nor reduced on mesh refinement.

The effective way of correcting this *approximability* local discretization error is to enrich the approximation spaces with additional deformation modes that enhance the desired capacities for representing embedded displacement and/or strain discontinu-

ities. On one hand, the E-FEM [29,10,30–36] and the X-FEM [37–39] strategies aim to represent strong discontinuities as such, via elemental or nodal enhancements of the displacement solution space. On the other hand, in practice both formulations are often applied in a regularized manner [40,41], and in these regularized versions, the discrete solution considers embedded strain localization bands rather than actual displacement discontinuities. The width of the regularized band is regarded as a numerical parameter of the implementation, chosen to be “small”. An obvious choice for this width is the size of the element, which, on mesh refinement, can be made as small as desired. This recovers the original idea of representing strong discontinuities in a smeared framework [42,43].

Both irreducible and mixed finite element formulations can be enhanced with a suitable enrichment technique for the displacement and/or strain fields to reduce the above discussed approximability error associated to the strain localization problem. In reference [44], the E-FEM approach is used together with a mixed displacement–pressure formulations to show improved approximation capabilities.

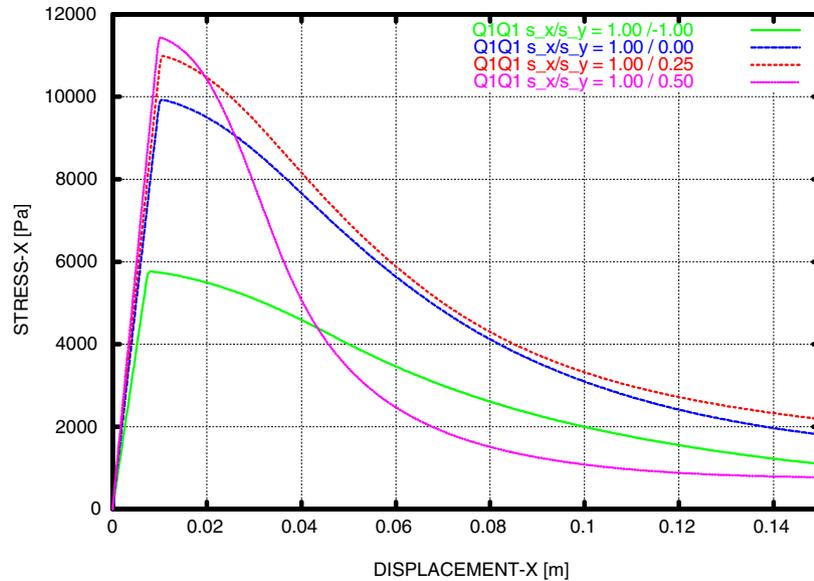
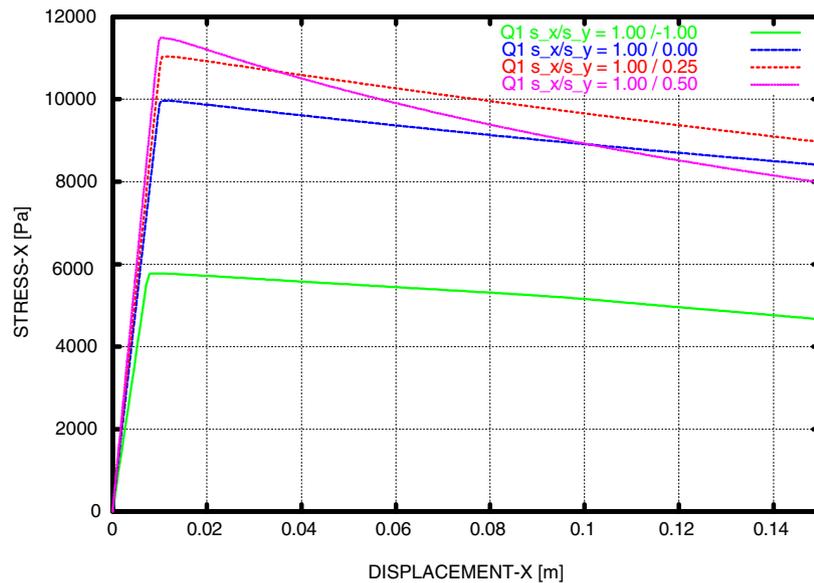
(a)  $Q1Q1$  mixed elements(b)  $Q1$  irreducible elements

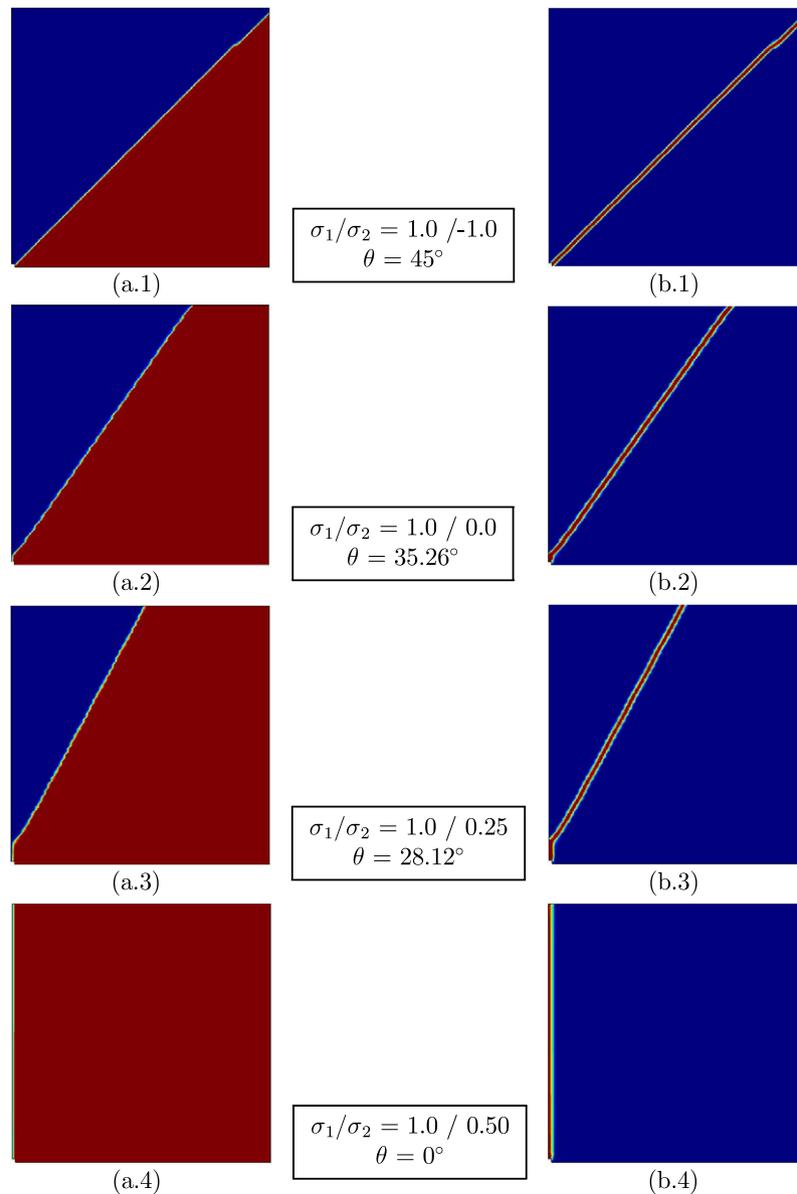
Fig. 12. Horizontal stress versus horizontal displacement for **plane stress** conditions with mixed and irreducible quadrilateral prism elements.

Using an enhanced formulation requires to specify the orientation of the modeled discontinuity. This poses the question of when, along the deformation process, calculating and fixing this orientation. If the bifurcation, localization, stress boundedness and decohesion conditions were fulfilled at the same time, that would be the instant to fix the discontinuity as a material surface; but this does not always happen. In general, a significant reorientation of the strain field may be needed until the plastic flow tensor has a structure compatible with the localization and decohesion conditions. Note that selecting the direction of the discontinuity according to some *ad hoc* condition and fixing it afterwards may become a superimposed condition on the constitutive behavior. Enhancing modes have not been used in this work, but the analysis in Section 3.2 shows that they should be introduced when Eq. (26) is satisfied.

## 6. Benchmark problems and numerical results

The numerical solution of the problem of bifurcation and localization discussed in the preceding sections is illustrated below in two selected benchmark problems. In both examples, strain localization is induced by the local  $J_2$ -plasticity model with exponential softening described in Section 2. Both plane stress and plane strain conditions are investigated. However, all computations are performed using a general 3D implementation, applied to a 3D solid domain with appropriate boundary conditions for each case considered. This ensures that the same implementation of the constitutive model is used for both plane stress and plane strain cases.

Relative performance of the irreducible displacement formulation and the stabilized mixed displacement/pressure formulation is tested considering meshes of *triangular* and *quadrilateral* prisms



**Fig. 13.** Results for **plane stress** conditions with *P1P1* mixed triangular prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

elements. The elements used will be: *Q1Q1* (bilinear displacement/bilinear pressure), *Q1* (bilinear displacement), *P1P1* (linear displacement/linear pressure), *P1* (linear displacement). Only low order elements are considered because they are more effective in problems involving sharp displacement and strain gradients. When the stabilized mixed displacement/pressure formulation is used, a value  $c = 0.1$  is taken for the evaluation of the stabilization parameter  $\tau_e$ .

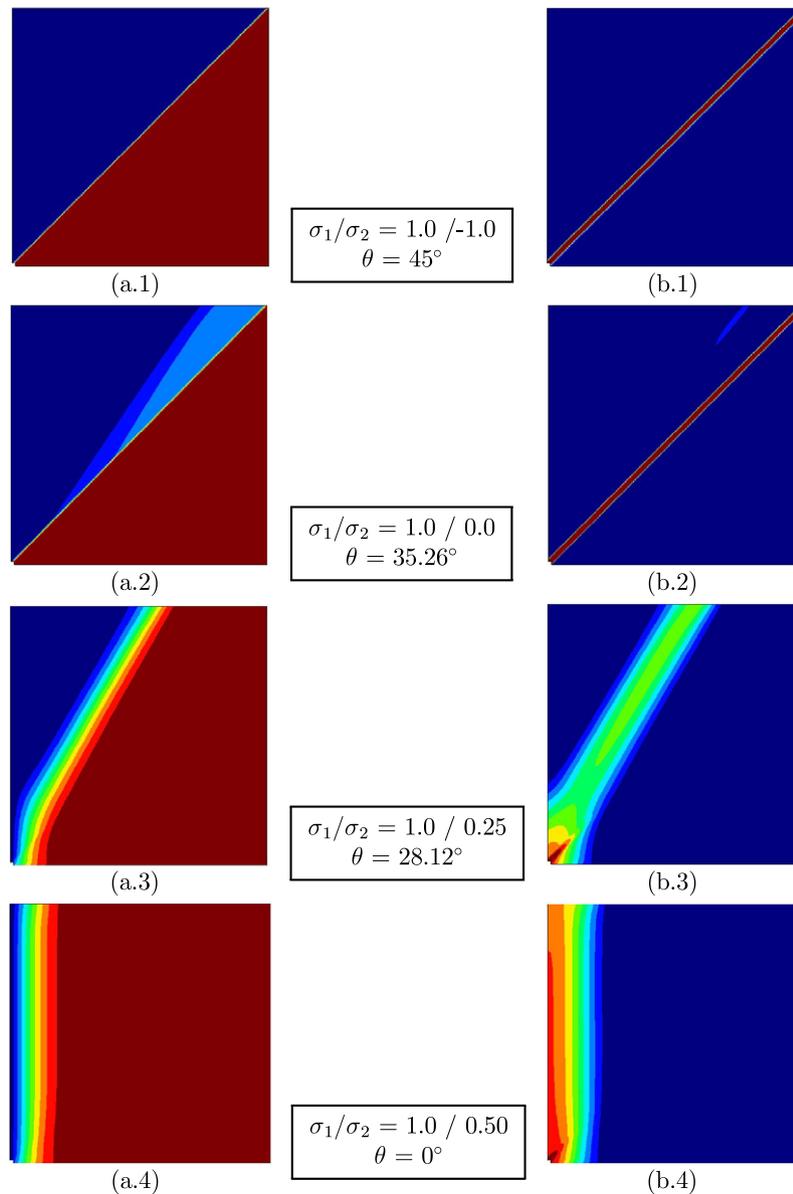
The following material properties are assumed: Young's modulus  $E = 10$  MPa, Poisson's ratio  $\nu = 0.3$  (recall that  $G = E/2(1 + \nu)$ ,  $K = E/3(1 - 2\nu)$ ), uniaxial yield stress  $\sigma_o = E/1000 = 10$  kPa and fracture energy  $\mathcal{G} = 300$  J/m<sup>2</sup>.

The geometry considered for the benchmark problems is depicted in Fig. 8. It consists of a square plate subjected to an imposed field of uniform horizontal ( $\sigma_x = \sigma_1$ ) and vertical ( $\sigma_y = \sigma_2$ ) normal stresses applied at the lateral boundaries. In-plane dimensions of the plate are  $20 \times 20$  m and its thickness is 0.125 m. In order to induce bifurcation and localization of the solution in a controlled fashion, a small imperfection is introduced in the form of a square opening of  $0.25 \times 0.25$  m  $\times$  m in the center of the plate.

Because of the double symmetry, only one quarter of the domain (the top right quarter) needs to be considered, with appropriate symmetry boundary conditions at the left and bottom boundaries.

In all of the analyses performed the square domain is discretized into a regular grid of  $h = 0.125$  m. The width of the localization band required for the softening regularization procedure described in Section 2 has been taken equal to this grid resolution  $b = h = 0.125$  m. The resulting 3D meshes are shown in Figs. 9a and b, composed of a uniform  $80 \times 80$  mesh of quadrilateral prisms and a uniform  $80 \times 80 \times 2$  mesh of rectangular triangular prisms, respectively. Notice that both meshes are structured: all of the element sides in the quadrilateral mesh are at  $0^\circ$  or  $90^\circ$  with the horizontal axis, all of the element sides in the triangular mesh are at  $0^\circ$ ,  $45^\circ$  or  $90^\circ$  with the horizontal axis.

The discrete problem is solved incrementally, in a (pseudo) time step-by-step manner. Analyses are performed under displacement control in order to trace the complete post-peak behavior. An automatic time incrementation procedure is used to reduce the size of the time steps when convergence due to the nonlinear effects is more difficult. About 200 steps are necessary to complete the anal-



**Fig. 14.** Results for **plane stress** conditions with *P1* irreducible triangular prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

yses. Within each step, a modified Newton–Raphson method, together with a line search procedure, is used to solve the corresponding non-linear system of equations. Convergence of a time step is attained when the ratio between the norm of the iterative and the incremental norm of the residual arrays is lower than  $10^{-3}$ .

It has to be remarked that no tracking algorithm of any sort has been used in any of the computations. Likewise, the analytical results obtained in Section 3.2 are not used in any way in the numerical computations; they are only referred to in this section for benchmarking purposes.

Calculations are performed with an enhanced version of the finite element program COMET [45], developed at the International Center for Numerical Methods in Engineering (CIMNE). Pre and post-processing is done with GiD, also developed at CIMNE [46].

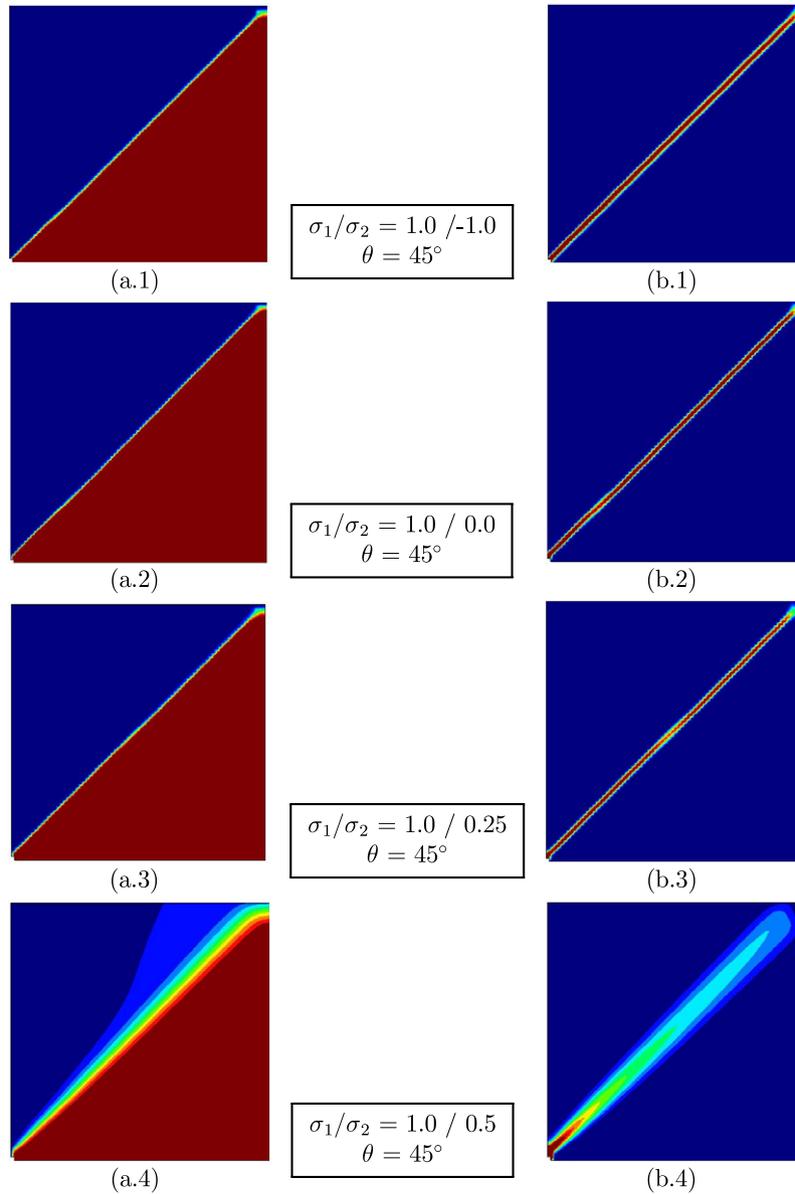
### 6.1. Plane stress conditions

In the first place, bifurcation and localization under plane stress conditions are investigated. To this end, displacements in the direction transversal to the plate are left free, save for one which is fixed in order to avoid rigid body motions.

#### 6.1.1. Quadrilateral prisms elements

Firstly, the performance of mixed Q1Q1 and irreducible Q1 quadrilateral prisms is examined. Figs. 10 and 11 report results for the mixed and the standard elements, respectively. In both figures, the four different rows correspond to the four different stress combinations investigated, which are the same ones depicted in Fig. 5 and the corresponding Table 2, namely: (a) **P1**:  $\sigma_1/\sigma_2 = 1.0/-1.0$ ,  $\theta = 45^\circ$ , (b) **P2**:  $\sigma_1/\sigma_2 = 1.0/0.0$ ,  $\theta = 35.26^\circ$ , (c) **P3**:  $\sigma_1/\sigma_2 = 1.0/0.25$ ,  $\theta = 28.12^\circ$ , (d) **P4**:  $\sigma_1/\sigma_2 = 1.0/0.50$ ,  $\theta = 0^\circ$ . The right hand side column in both Figures shows contours for horizontal displacements once the localization band is fully developed, while the right hand side column displays corresponding contours for the equivalent plastic strain.

It is clear in Fig. 10, that the mixed quadrilateral elements are capable of solving the bifurcation and localization problem under plane stress conditions rather satisfactorily. For load case **P1**, pure shear, an exact angle of  $\theta = 45^\circ$  is obtained, and the simulated slip line bifurcates near the top right corner because of the perfectly symmetric boundary conditions. For load cases **P2** and **P3**, the obtained direction for the localization differ from the analytical values in less than  $1^\circ$ . Only a slight deviation from this occurs in the



**Fig. 15.** Results for **plane strain** conditions with *Q1Q1* mixed quadrilateral prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

vicinity of the central opening; this can be partly attributed to the effect of the disturbed field and partly to a minor mesh bias. For load case **P4**, the localization direction is again exact.

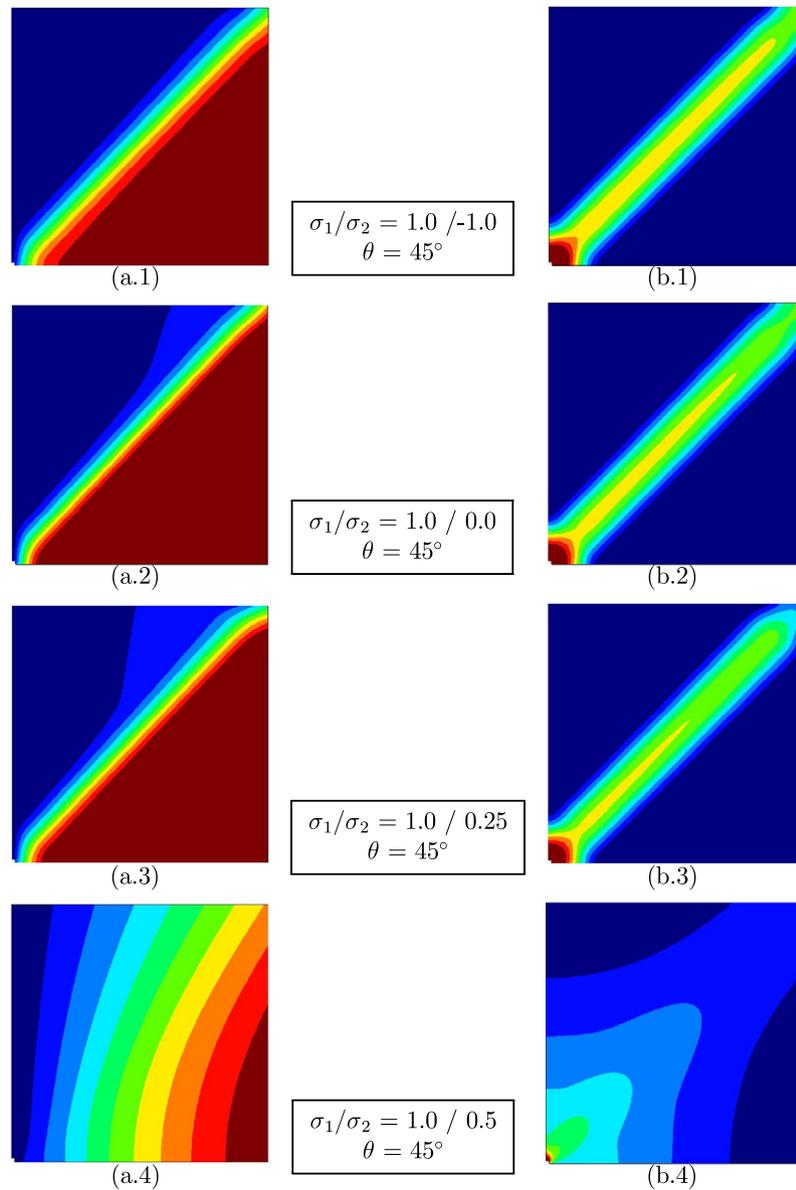
It is remarkable that with the same constitutive behavior, namely a purely isochoric plastic model, it is possible to obtain from a pure mode II response (relative displacement across the localization band **w** orthogonal to the normal to the band **n**), like in the **P1** case, to a pure mode I response (relative displacement across the localization band **w** parallel to the normal to the band **n**), like in the **P4** case; and, naturally, mixed mode responses in between.

Note the resolution of the discontinuity surfaces achieved by the finite element solution is optimal for the displacement and strain interpolations used: the strong discontinuity is regularized into a band which is only one element across.

Fig. 11 shows results obtained with the irreducible quadrilateral prisms Q1. The standard formulation is able to solve correctly the bifurcation and discontinuous bifurcation conditions, but clearly unable to comply with the decohesion condition. For the four depicted situations strain localization bands form at the angles pre-

dicted by the analytical results in Section 3.2. This is not surprising because, in this benchmark setting, the far field stress state is exactly provided by the applied boundary conditions. However, the volumetric locking that accompanies (plastic) strain localization makes it impossible for the band to collapse into a regularized strong discontinuity that approaches the decohesive limit asymptotically.

Fig. 12a and b render plots of applied  $\sigma_x$  versus horizontal displacement at the right bottom point of the studies quarter plate for the mixed and irreducible quadrilateral elements, respectively. As commented in Section 3.2.1, under plane stress situations, the onset of yielding, bifurcation and localization occur at the same instant. Also, from the same moment at which plastic flow is initiated this manifests in a direction that is compatible with the decohesion condition. On one hand, these facts are clear in the top Figure, which shows curves corresponding to well developed failure mechanisms. The limit cases: **P1** for mode II and **P4** for mode I are particularly interesting. On the other hand, the bottom Fig. 12b clearly shows the locking volumetric effect inherent to irreducible low order elements in quasi-incompressible situations.



**Fig. 16.** Results for **plane strain** conditions with *Q1* irreducible quadrilateral prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

The bifurcation and localization points are reached correctly, because they depend only on the elastic regime, and this is well resolved by the mesh. However, volumetric locking induced by the isochoric character of the plastic flow distorts the strain field in such a manner that the decohesion condition cannot be fulfilled.

#### 6.1.2. Triangular prisms elements

Secondly, the performance of mixed *P1P1* and irreducible *P1* triangular prisms is examined. Figs. 13 and 14 report results for the mixed and the standard elements, respectively. The same stress combinations as in the previous Section are investigated.

Fig. 13 shows that the mixed triangular elements solve the bifurcation and localization problem under plane stress conditions in the same adequate manner than their quadrilateral counterparts. Their respective results are indistinguishable. On its part, Fig. 14 shows that the irreducible triangular elements have similar shortcomings as their quadrilateral companions. However, some differences may be found between Figs. 11 and 14. For the pure shear case,  $\sigma_1/\sigma_2 = 1.0 / -1.0$ , the irreducible triangles do manage to yield the correct solution. This befalls because the used finite

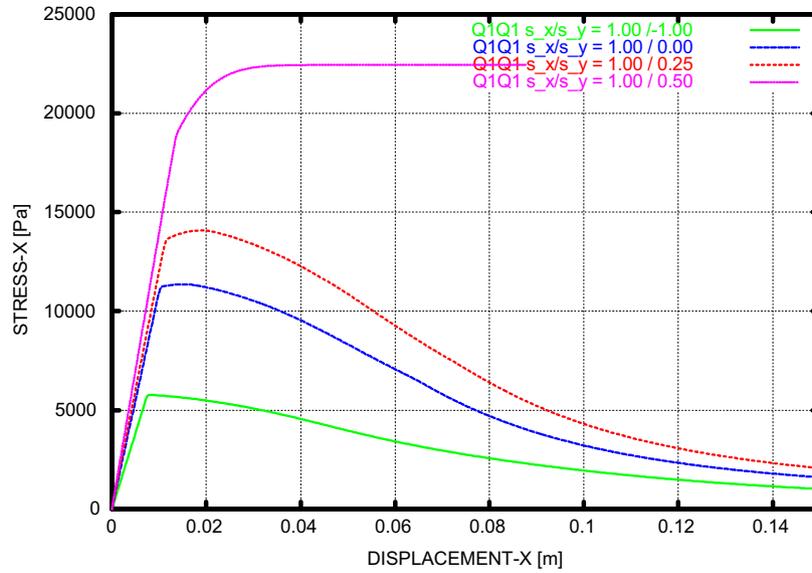
element mesh happens to be perfectly aligned with the correct localization direction. For uniaxial tension,  $\sigma_1/\sigma_2 = 1.0/0.0$ , another interesting feature can be observed, the mesh initiates smeared localization in the correct direction, but eventually mesh-bias takes over and a sharp localization happens, but at the wrong direction. For the other two cases, results are indistinguishable from those of the quadrilaterals, strongly affected by volumetric strain locking.

#### 6.2. Plane strain conditions

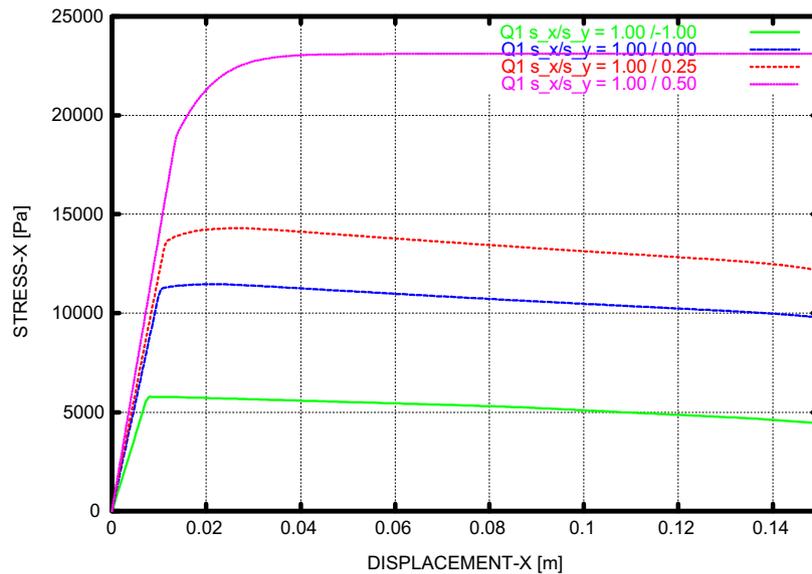
In the second place, bifurcation and localization under plane strain conditions are investigated. To this end, displacements in the direction transversal to the plate are all fixed equal to zero; this ensures that normal strain in that direction is exactly equal to zero.

##### 6.2.1. Quadrilateral prisms elements

The performance of mixed *Q1Q1* and irreducible *Q1* quadrilateral prisms is examined first. Figs. 15 and 16 report results for the mixed and the standard elements, respectively. In both figures, the



(a) Q1Q1 mixed elements



(b) Q1 irreducible elements

Fig. 17. Horizontal stress versus horizontal displacement for plane strain conditions with mixed and irreducible quadrilateral prism elements.

four different rows correspond to the four different stress combinations investigated, which are the same ones depicted in Fig. 6 and the corresponding Table 3, namely: (a) **P1** :  $\sigma_1/\sigma_2 = 1.0 / -1.0$ , (b) **P2** :  $\sigma_1/\sigma_2 = 1.0/0.0$ , (c) **P3** :  $\sigma_1/\sigma_2 = 1.0/0.25$ , (d) **P4** :  $\sigma_1/\sigma_2 = 1.0/0.50$ . In all cases, the localization angle is identical,  $\theta = 45^\circ$ . The right hand side column in both Figures shows contours for horizontal displacements once the localization band is fully developed, while the right hand side column displays corresponding contours for the equivalent plastic strain.

Figs. 15 and 16 show that the bifurcation and localization problem is more demanding on finite elements under plane strain conditions than in a plane stress situation. This is because for the decohesion condition to be met and a regularized strong discontinuity to develop, a significant amount of strain reorientation has to occur through the growth of plastic flow.

Fig. 15 proves that the mixed quadrilateral elements are capable of reproducing the necessary reorientation of the strain flow in all

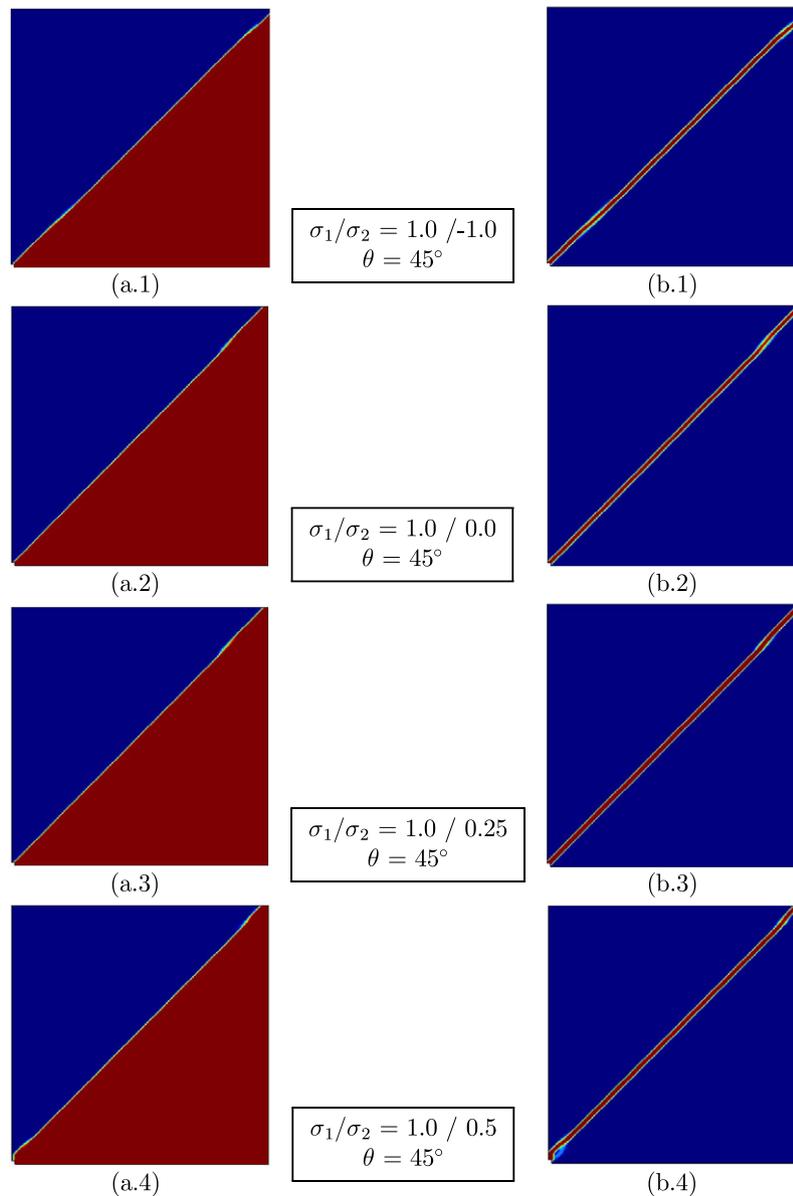
but the most difficult case, **P4**. In the first three cases, the (regularized) strong discontinuity is correctly formed, but in the last fourth case, the mesh is too rigid to allow for the collapse of the localization band, which forms at the correct direction, into a discontinuity with no traction cohesion. The situation is far worse in Fig. 16, which shows that the irreducible quadrilateral elements cannot properly localize strains in any of the tested cases. In the last case, not even a smeared localization band is visible in the displacement and plastic strain contour plots.

Figs. 17a and b are consistent with these explanations.

### 6.2.2. Triangular prisms elements

Finally, the performance of mixed P1P1 and irreducible P1 triangular prisms is examined. Figs. 18 and 19 report the corresponding results.

On one hand, Fig. 18 shows that the mixed triangular elements solve the demanding bifurcation and localization problem under



**Fig. 18.** Results for **plane strain** conditions with *P1P1* with mixed triangular prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

plane strain conditions slightly better than their quadrilateral counterparts. Comparing these with results in Fig. 15, it is perceived that mixed triangular elements solve satisfactorily all the cases considered. This is because the triangular mesh is more flexible than the quadrilateral one, and particularly for the deformation mode called for in these tests.

On the other hand, Fig. 19 depicts an unreliably adequate performance by the irreducible triangular elements in this test. This is because the used finite element mesh happens to be perfectly aligned with the correct localization direction. The plotted results, considered together with the ones obtained in the previous cases, serve to underline that the irreducible formulation is unacceptably mesh-dependent.

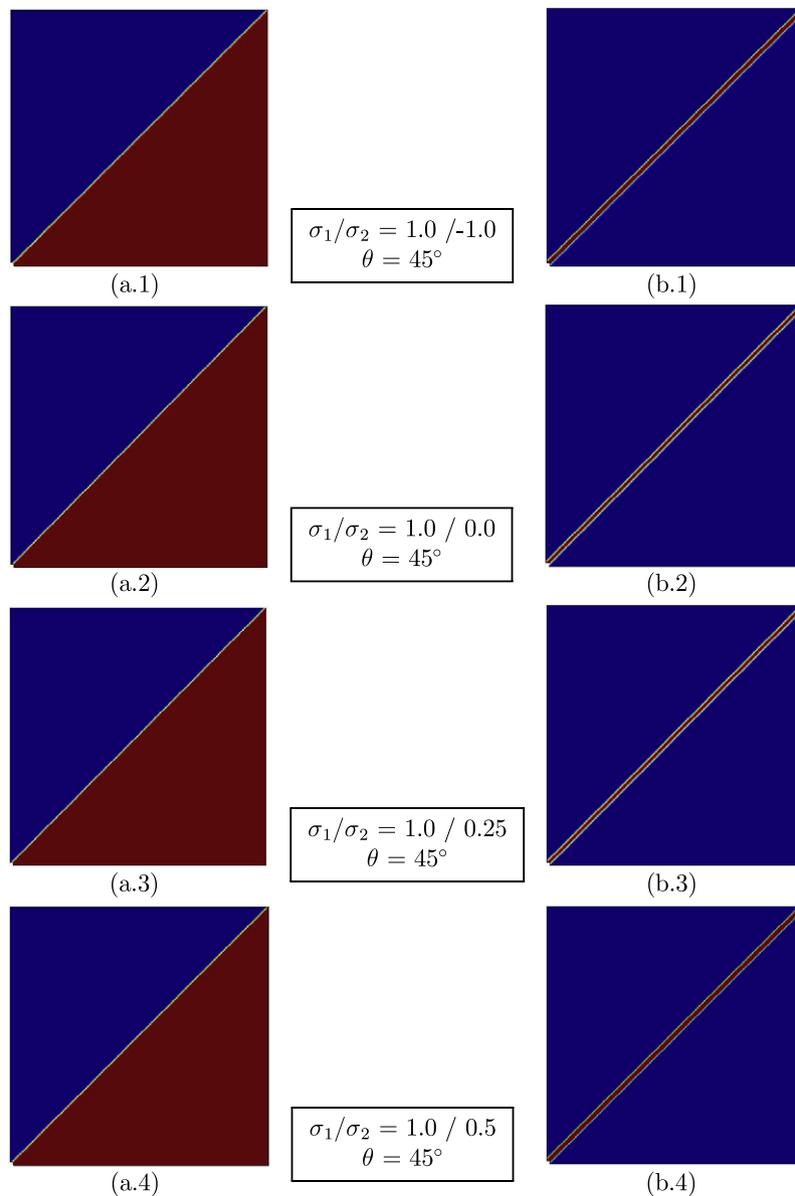
## 7. Conclusions

This paper considers the problem of strain bifurcation and localization in  $J_2$  plasticity under plane stress and plane strain conditions.

First, distinction is made among the analytical necessary bifurcation, localization, stress boundedness and decohesion conditions. On one hand, this shows that results from classical localization analysis do not in general guarantee that the decohesion limit may be reached; on the other hand, localization angles can be obtained by directly imposing this condition.

Second, the irreducible (displacement) and mixed (displacement/pressure) formulations are considered for the solution of the associated discrete problem, characterized by the isochoric nature of the purely deviatoric plastic flow. Stabilization is necessary for the case or using equal order interpolating spaces for displacements and pressure. Even if not specifically designed for this purpose, the mixed formulation reduces the approximability error that low order elements display when reproducing (regularized) discontinuous displacement fields, if the direction of the discontinuity is not parallel to one of the element sides.

Numerical examples demonstrate the relative performance of the mixed and irreducible quadrilateral and triangular (prisms) elements subjected to plane stress and plane strain conditions.



**Fig. 19.** Results for **plane strain** conditions with *P1* with irreducible triangular prism elements. Contours for: (a) horizontal displacement and (b) equivalent plastic strain.

Without the help of any sort of tracking algorithm or the analytical results obtained previously, the mixed displacement/pressure formulation shows an ample superiority over the irreducible one to predict correct failure mechanisms with localized patterns of plastic deformation, which are practically free from dependence of the mesh directional bias in all but the most demanding cases. Contrariwise, irreducible elements suffer strongly from volumetric strain locking as soon as plastic behavior appears and this precludes shear strain localization and therefore, shear bands fails to collapse in true failure mechanisms. In the limited cases in which the failure mechanism actually forms, it is very much affected by the mesh bias. Only when the mesh is well aligned with the correct failure mechanism (unreliably) adequate results are obtained.

### Acknowledgments

Financial support from the Spanish Ministry for Education and Science under the *SEDUREC* project (CSD2006-00060) is also acknowledged.

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