CHAPTER III

AN APPRAISAL OF JOINT ELEMENTS

3.1 GENERAL

In recent years a number of joint elements have been evolved and developed in the context of numerical methods particularly the Finite Element, in order to analyse the behaviour of junctions or interfaces in structural and geological materials. The chronological development of joint elements is described in Table 3.1. The principal joint elements are developed by Goodman (1968), Zienkiewicz (1970), Ghaboussi (1973), Herrman (1978), Katona (1981), Heuze (1982) and Desai (1984). The principal characteristics of some of the well discussed joint elements are presented in the following paras.

3.2 JOINT ELEMENT PROPOSED BY GOODMAN (1968)

Goodman (1968) was the first to initiate a concept of 'joint element' for the analysis of jointed rocks. His joint element is characterized by joint stiffness in normal direction (Kn), joint stiffness in tangential direction (Ks) and joint shear strength (S). His joint element is four noded having zero initial thickness. The joint element stiffness matrix is constructed for each joint element in a subroutine called "joint stiff". The structural stiffness matrix for the entire system of blocks and joints is then assembled by adding the appropriate terms of elements contributing stiffness, be they of joints or continuum elements, at each nodal point in turn by direct stiffness method. After solution of the stiffness equations, the joint stresses are calculated from the known displacements in subroutine called 'joint stress'. If the joint normal stress is tensile in any element, both Ks and Kn are set equal to zero for the element and the

TABLE 3.1 : CHRONOLOGY OF DEVELOPMENT OF JOINT ELEMENTS

Author, Year	Geometry			No thickness	Rotation stiffness	Dilation	Strain softening
	Plane	Axi-symmetric	Three dimensional				
1	2	3	4	5	6	7	8
Goodman, 1968	*			*			
Mehtab, 1970			*	*			
Heuze, 1971	*		*				*
Noorishad, 1971	*			*			
Heuze, 1971	*			*		*[a]	*
St. John, 1972	*		*	*			
de Rouvray, 1972	*			*		*[a]	*
Goodman, 1972	*			*		*[a]	*[c]
Ghaboussi, 1973	*[b]	*				*[a]	
Gale, 1974	*			*			
Ngo, 1975	*			*			
Sharma, 1976	*						
Hiber, 1976	*						
Goodman, 1977	*			*		*[a]	*
Hittinger, 1978	*			*	*	*[a]	*
Heuze, 1979	*			*	*	*[a]	
Xiurum, 1981	*			*		*[a]	
Van Dillen, 1981	*		*			*[a]	

*[a] - No explicit coupling between opening and reclosing tendencies

*[b] - Element, singular at some orientations

*[c] - Iteration by load transfer.

problem is repeated. Also the joint cohesion, joint friction and residual tangential stiffness are read in as data and the shear strength is calculated for the indicated normal pressure on each joint. If the joint shear stress exceeds the shear strength, then Ks is set equal to Ks residual and the problem is repeated. The joint element proposed by Goodman (1968), however, exhibit an unrealistic aspect wherein adjacent blocks of continuous elements penetrate into each other. Zienkiewicz et al (1970) suggested an isoparametric finite element formulation for an interface element which treated the discontinuity essentially like a solid element.

3.3 JOINT ELEMENT PROPOSED BY GHABOUSSI et al (1973)

With the joint element advocated by Zienkiewicz (1970), numerical difficulties arose from ill conditioning of the stiffness matrix due to very large off diagonal terms or very small diagonal terms generated by this element in certain cases. To avoid this theoretical difficulty and yet to be able to represent a wide range of joint properties including positive or negative dilation, Ghaboussi described a discrete finite element for joints.

The joint element uses relative displacements as the independent degree of freedom. The displacement degrees of freedom of one side of the slip surface are transformed into the relative displacements between the two sides of the slip surface. The relative normal and tangential displacements ΔUn and ΔUs are assumed to vary linearly along the element. In case of debonding, the joint element is physically non existant and disappears from the assembly of the global stiffness matrix. In case of contact, the relative displacements in the direction normal to the joint plane are zero. Dilatancy is represented by adopting strain hardening theory of plasticity which uses a perfectly plastic yield surface to limit shear stresses and a strain hardening cap to control dilatancy.

3.4 JOINT ELEMENT PROPOSED BY HEUZE (1982)

To remedy some of the shortcomings of the then available joint elements, Heuze (1982) made two new developments in the modelling of the geological discontinuities. An axisymmetric joint element has been formulated. It is operational at all orientations unlike some of the previous formulations. The stiffness matrix of the joint does not contain diagonal terms. However, the element still can represent dilatancy due to shear, by virtue of the new model which is proposed for dilatant joint effects.

The second development involves the ability to calculate the increase in joint normal stress due to an increment of shear displacement. In the formulations proposed by other investigators, the stiffness coefficients are indicated to be internal properties of the joint which supposedly could be determined in direct shear tests. However, the approach ignores the stiffness of the materials transverse to the direction of shear. For a given joint, at a given starting normal stress, the normal stress increase due to a shear displacement certainly depends on how stiff the medium adjacent to the joint is. In particular (Kns) which relates to the dilatant shear effect, must be a function of stiffnes of the adjacent medium. This means that to obtain representative dilatant joint effects for a given field situation, the shear testing system would have to be of the same transverse stiffness as the stiffness of the adjacent rock in the field. This is a prohibitive requirement, because this transverse stiffness would have to be determined in the field for each joint to be modelled. Value of (Ksn) and (Kns) are yet not published anywhere in the literature. Therefore an explicit approach is proposed in which the stiffness matrix of the joint does not have diagonal terms and d is calculated explicitly. This new uncoupled approach can be used for joints of any geometry, i.e. plane, axisymmetric or three dimensional. Also it permits using conventional direct shear testing. The new axisymmetric joint element is formulated in two independent ways, which give the same result.

(a) A direct joint formulation starting from a strain-displacement relation with a vanishing joint thickness.

(b) A formulation starting from a transversely isotropic rectangle in a material with zero Poisson's ratio and a vanishing element thickness.

3.5 JOINT ELEMENT PROPOSED BY DESAI (1984)

In most of the elements proposed before Desai (1984), the shear behaviour is simulated as nonlinear elastic or plastic and the shear stiffness is evaluated as a tangent modulus from laboratory stress/strain behaviour in direct shear tests. Based on the assumption that the structural and geological media do not overlap at interfaces, a high value, of the order of 10^8 to 10^{12} units, is assigned for the normal stiffness Kn. There is no logical basis for adoption of such values which need to be determined for the problem on hand by performing parametric studies. Furthermore, in most problems, the formulation can provide satisfactory solutions for stick (or no slip or bonded) and slip modes for which the normal stress remains compressive. For other modes such as debonding, the solutions are often unreliable. Since the proposed element essentially represents a solid element of small finite thickness and since it can represent a thin layer of material between two bodies it is referred to as a thin layer element. The element is treated essentially like any other solid element. A basic assumption made is that the behaviour near the interface involves a finite thin zone rather than a zero thickness as assumed in previous elements. Since the interface is surrounded by the structural and geological materials, its normal properties during the deformation process must be dependent upon the characteristics of the thin interface zone as well as the state of stress and properties of the surrounding elements. Thin layer interface element can be formulated by assuming it to be linear elastic, non-linear elastic or elastic-plastic. The development of its stiffness characteristics follow essentially the same procedure as solid elements. For two dimensional plane strain idealization the special form of (C^e) and its inverse form (D^e) are given as :

$$(C^e) = \begin{bmatrix} C_1 & C_2 & 0 \\ C_2 & C_1 & 0 \\ 0 & 0 & G_1 \end{bmatrix} \qquad (3.1)$$

and

$$(D^e) = \begin{bmatrix} \frac{1-\nu^2}{E} & \frac{-\nu(1+\nu)}{E} & 0 \\ \frac{-\nu(1+\nu)}{E} & \frac{1-\nu^2}{E} & 0 \\ 0 & 0 & \frac{1}{G_1} \end{bmatrix} \qquad (3.2)$$

For nonlinear elastic behaviour such as hyperbolic simulation, E, ν and G can be defined as variable moduli based on triaxial and direct shear tests.

From a preliminary study, it is concluded that satisfactory simulation of interface behaviour can be obtained for t/B ratio in the range of 0.01 to 0.1.

3.6 CONCLUDING REMARKS

From the appraisal of joint elements it is seen that the joint element proposed by Goodman is having zero initial thickness whereas Zienkiewicz proposed an interface element which is treated like other solid elements. Heuze postulated a joint element with vanishing thickness whereas Desai followed a concept similar to Zienkiewicz. His interface element is also treated like a solid element having very small thickness.

It is further observed that joint element proposed by Ghaboussi is physically non-existant in case of debonding and it disappears from the assembly of the global stiffness matrix. Dilatancy is represented by adopting strain hardening theory.

The joint element proposed by Heuze is capable of calculating the increase in joint normal stress due to dilation.

However, none of these joint elements incorporate the phenomenon of dilation in direct terms and develop the approach from first principles.