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A survey on finite element modelling of steel end-plate connections

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Summary

End-plate connections represent the joint types more widely studied in literature. This paper aims to present a complete review of finite element modelling of this joint type. After a general classification and presentation of the criterions for evaluating the models, according to the type of chosen finite element, the models will be discussed in four different categories : Plane stress, plate bending, shell and solid element models. Conclusion, perspective and a brief presentation of our laboratory 3D model, are included in the last paragraph.

1-Introduction

During the last ten years, experimental and theoretical researches have provided a lot of results and the concept of semi-rigidity has gradually entered in standards. The number of geometrical and mechanical parameters that can reasonably be expected to influence the joint behaviour is significant, but the experimental studies provide rather limited information. Thus, the Finite Element Method (F.E.M.), represents the most suitable tool for conducting a such exhaustive investigation. Furthermore, the results of this method could be a rational background for Eurocode standards. Because of important development of software and hardware in recent years, the progress in studying the semi-rigid connection has been fast and needs to be analysed.

Nethercot & Zandonini (1988) were the first to present a chronological analysis in this field . Among several joints, the end-plate connection deserves a special attention and we can find a lot of researches on it . Thus this paper is devoted to this type of joint and try to have a new point of view on the results published until 1995 .

There are several ways to classify the F.E. models : 1- Type of joint (bolted, welded), 2- Material behaviour law (elastic, elasto-plastic) 3- Finite element type (plane stress, plate bending, shell, solid), 4- Applied loading (monotonic, cyclic). For simplicity, we choose the third case for discussing the bolted joint and specially the end-plate connection . Referring to Fig. 1(standard end-plate joint), we notice that there are four possibilities for modelling a connection :
1- Modelling on the surface of Y-Z axis, using plane stress element. 2- Modelling on the surface of X-Z axis, using plane stress element. 3- Modelling on the surface of X-Y axis,

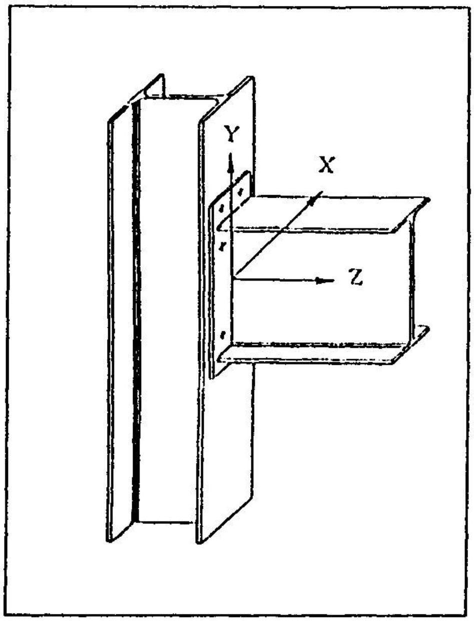

Figure 1- Standard end-Plate joint

Researchers	Year	Country	Model	Programme
Krishnamurthy	1976	USA	plane str.* & solid	
Ioannides & Tarpy	1979	USA	plate ben.**	
Ahuja	1982	USA	solid	
Ghassemieh	1983	USA	solid	
Jenkins &Tong	1986	UK	plate ben.	
Kukreti	1987	USA	plane str. & solid	
Colson	1989	France	plane str.	
Rothert	1992	Germany	solid	Prothec
Ziomek	1992	Poland	shell	Algor
Chasten	1992	USA	shell	Adina
Bursi	1993 & 94 & 95	Italy	shell & solid	Adina & Abaqus
Gebbeken	1994	Germany	plane str.	Prothec
Bahaari	1994	Canada	plane str.	Ansys
Sherbourn	1994	Canada	shell	Ansys
Masika	1995	Hungary	plane str.	
Nemati & Le Houedec	1996	France	solid	Samcef

* Plane stress elment ** plate bending element

Table 1- F.E. Models

using plate bending or shell elements 4- Three dimensional modelling . In this case we can use the shell element, the solid element or the combination of all kind of element (beam and shell elements, or shell and solid elements, etc...)

Table 1 gives the list of researches. From this table we can conclude that in recent years the European are more interested to this joint type. Furthermore, it appears more popular to use general codes.

2- Criterion of analysis

The comparison between the actual behaviour of joints and the behaviour of proposed models could be analysed from two points of view : 1- Final results 2- Phenomenon Modelling . It is obvious that the method for modelling the existing phenomena, changes the final result. The complete list of phenomena and the expected detail of results, allow us to evaluate the models .

2-1 Criterion based on final results

Moment rotation curve is the final product of a complex interaction between the member components. Thus a complete result includes the following characteristics :

A- Global behaviour of joint (i.e. moment-rotation curve) :

1- initial stiffness 2- plastic moment 3- hardening slope 4- ultimate moment
B- Local behaviour of components (force, displacement, stress, strain) :
1- bolts 2- plate 3-web and flange of beam 4-web and flange of column 5- welding etc...

2-2 Criterion based on phenomenon modelling

By taking into account the actual phenomena, simplification or neglecting some characteristics could be an important criterion . Generally, a complete model includes these characteristics :
A- Physical characteristics :
1- material and geometrical non-linearity and slope of hardening branch 2- hardening law (kinematic, isoparametric, mixed.) 3- effect of welding on material behaviour 4-buckling
B- Boundary conditions :
1- contact with or without friction : bolt head and plate, bolt shank and plate, plate and flange 2- type of loading : pure moment, shear force
C- Initial state :
1- initial displacement 2- preloading of bolts 3- residual stresses
D- Numerical characteristics :
1- type of element for each member 2- integration

3- Analysis

3-1 Plane stress element

In this study several types of plane stress element are used. Fig. 2 shows a summary of eight researches in this field with following explanations :

3-1-1 Modelling on the surface of Y-Z axis
This model consists to model the joint on the surface of beam and column webs. Hence, the biaxial applied moment is simplified by a linear distribution force on the surface of beam. All the geometrical depth must be taken into account in this surface. This object is achieved by two different approaches; in the first one, the thickness of elements is taken equal to the depth of related component in X direction. The second method uses an homogenisation technique by means of applying different Young's moduli for each member to find the proper thickness.

Krishnamurthy (1976),Fig. 2-a, *Kukreti (1987)*,Fig. 2-b,*Gebbeken (1994)*,Fig.2-g *and Bahari (1994)*,Fig. 2-c, used the first approach and *Colson (1989)*,Fig.2-d, applied the second . In almost of researches, the column is supposed rigid and the bolt head and welding effect are neglected . If we suppose the model of *Krishnamurthy* as a reference which used elastic-perfectly-plastic material, applied the bolt force using an initial displacement and modelled the contact by means of an iteration procedure for detecting the attachment, we can say that *Kukreti* followed exactly the same model. *Gebbeken* added the hardening material. *Bahari* added column, interface element for contact and bilinear and trilinear material models for plate and bolts, respectively .

The finding of this type of analysis is limited to : initial stiffness, ultimate moment, qualitative moment-rotation curve which can show the effect of thickness and the estimation of prying forces. However, with the parametric study of 2D model and finding the correlation factor between 2D and 3D, *Krishnamurthy* proposed his famous designe formula for AISC.

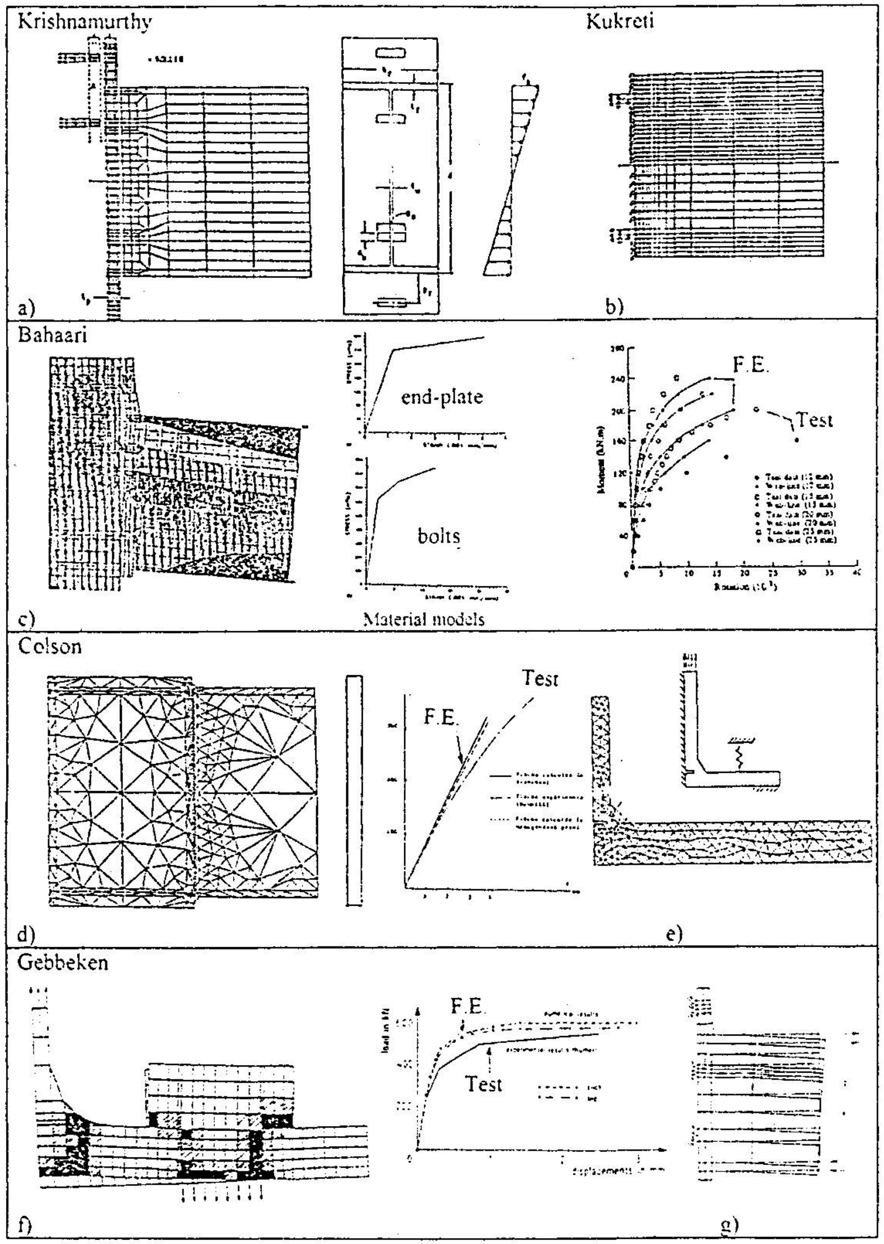

Figure 2-Plane stress models

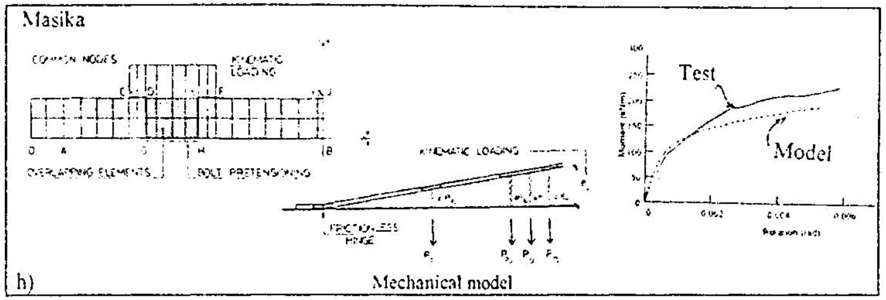

Figure 2-continue

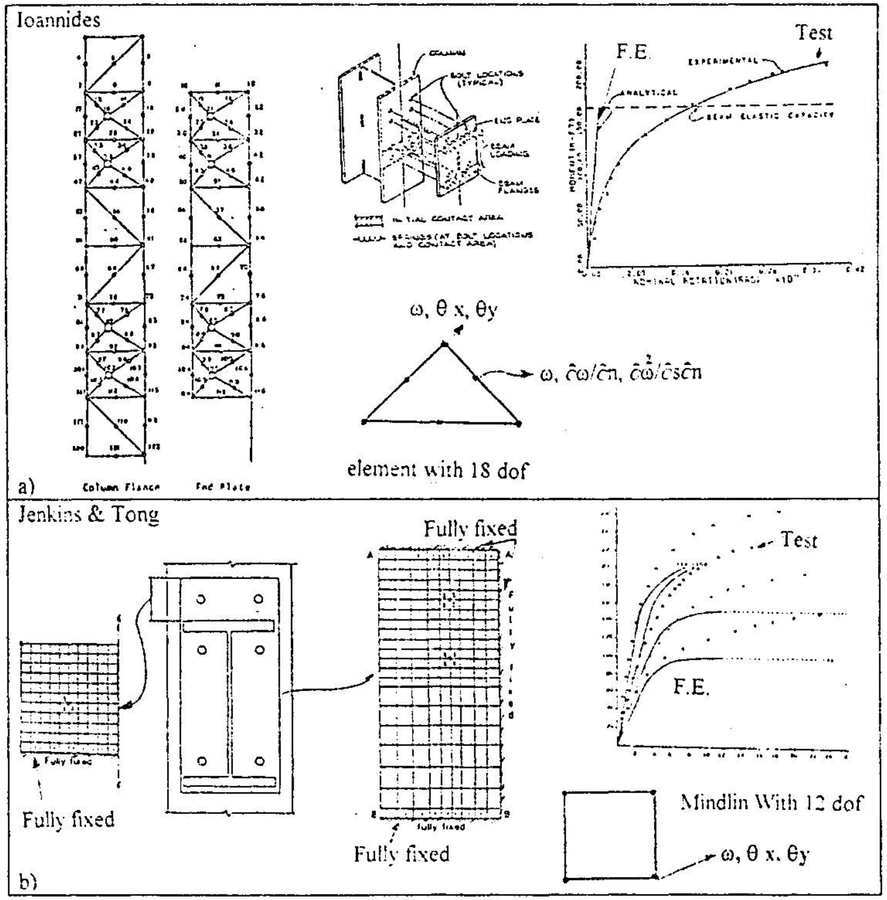

Figure 3-Plate bending models

3-1-2 Modelling on the surface of X-Z axis
This type of modelling consists to model the joint on horizontal plane. In this plane, end-plate and related beam web could be consider as a T-stub. The column flange and its web have the same shape (T-stub). Thus, by using the plane of symmetry, we can study a half of a T-stub .

Colson (1989) for finding the initial stiffness of an end-plate attached to a rigid foundation, used a new point of view . In this model, the bolts are replaced by a spring (Fig. 2-e). The assumption of non penetration welding is applied by introducing a crack between the welded line and flange . The results appear to be satisfactory .

Gebbeken (1994) studied the column flange with assumption of rigid end-plate. The procedure of study is the same as *Krishnamurthy*'s one by adding the bolt head and a frictionless slippage between the bolt head and flange . This study shows that introduction of contact between the bolt head and the related plate (here flange) changes seriously the results, Fig. 2-f .

Masika & al (1995) used a combination of F.E. method and mechanical model to find the global response of an end-plate haunched joint . The complete joint is divided to several independent T-stubs which are replaced by springs. The improvements of this method are: 1- combined kinematic and isotropic hardening laws 2- geometrical non-linearity 3- introduction of the failure mode by a given upper limit of the effective plastic strain. Unfortunately, there is no any direct comparison between T-stub results and test results to confirm this sophisticated modelling . Fig. 2-h shows a global behaviour of joint compared with experience .

In comparison with Y-Z surface (web) this model could be more realistic because the loading is really due to column web . The disadvantage is the neglect of interaction effect of neighbour T-stubs. Except some local results like initial stiffnes, effect of friction, slippage of bolt head, there is no direct result for joint. The spring model could represent an intermediate step to find the global response.

3-2 Plate bending element

In this method, the joint is modelled on the surface of the end-plate which involves neglecting the effect of beam .
Ioannides & Tarpy (1978) studied the interaction between end-plate and column flange . Each surface is modelled by a special triangular element (Fig. 3-a). The moment rotation is not satisfactory because the elastic-plastic material properties have not been included . However the effect of end-plate thickness on the column flange behaviour and displacement variation of end-plate are demonstrated qualitatively.

Jenkins, Tong & al (1986) studied the joint in two steps. In the first step, the modelling of Ioannides was followed (by adding the column web) and the prying force was estimated as much as 15% of applied force. In the second step, the end plate was divided on two independent plates with special boundary conditions illustrated in Fig.3-b .The moment-rotation curve is found by applying the displacement in the centre of bolts. By using the equilibrium equation and force-displacement of bolt (found in the last step) the applied moment could be found. The moment rotation results are softer than test results
We can notice that the nature of this type of modelling needs the simplification of boundary conditions, bolts, loading etc...and, consequently, it reduces the effectiveness of model.

3-3 Shell element

Because of existence of several components in a joint, it is not possible to use the shell element alone . For example the bolts are cylinders and in the perpendicular direction of end-plate. Thus, the use of other types of elements like beam element, solid element etc.. seems to be necessary. In this field we can find five independent researches which were done in last five years .
Devies & al (1990) designed a model for a frame with end-plate haunched connection . A complete frame is represented by shell element and the bolts with elastic beam element. In this research, the attention was paid to the global frame behaviour and to the possibility of local and member buckling. Hence the end-plate connection was not investigated in detail.

Ziomek & al (1992) conducted a study to find the effect of several numerical and physical parameters on one thin end-plate (thickness=12 mm, Fig.4-b) using the ALGOR programme. They concluded that modelling the material properties (choice of hardening law), bolts, finite element mesh as well as number of integration points, strongly influence results . The influence of geometrical non-linearity is rather small in this special case .

Chasten & al (1992) proposed a model with the code ADINA, for two end-plates with 19 and 25 mm of thickness in two phases. The first phase was the same as Ziomek's model by substitution the beam web with plane stress elements to find the transmitted force to end-plate. In the second phase, only the extended part of end-plate was studied. The bolts forces founded in this phase are reasonable(Fig. 4-a).

Bursi & al (1993)
This research is the same as the second phase of Chasten's model, but for extended and inner part of end-plate using the same code. The results of moment-rotation curve are more stronger than test result even for thinner end-plate with 12 mm of thickness.

The most complete research in this field belongs to *Sherbourn &t al (1994)*. By using the ANSYS code, a complete joint (with column) was modelled. The main difference of this work and the previous mentioned shell models is the modelling of bolts . To take into account the effect of bolt head and nut, they are idealised by isoparametric solid elements . The bolt shanks were substituted with six truss elements . The interface elements are used for solving the contact problem . The material properties are the same as their 2D works (*Bahaari & al*) . The results are satisfactory for thin end-plate . By increasing the thickness of end-plate, the shell element shows a little soft results (Fig.4-c). The prying action is plotted for some joints. It is important to mention that they used the nominal yield stress instead of actual one, which could influence the results i.e. more stronger moment-rotation curve.

3-4 Solid element

The solid elements are the natural selection for a 3D F.E. model, but the accuracy and the domain of application of model depend strictly on the simplifications, considered hypothesis and the type of element. In this field, there are seven works :

Krishnamurthy(1976) is again the first to use the solid element for end-plate connection but only with an elastic material . The maximum applied load is 0.6 time the yield stress . The element is a Levy's superparametric 33 dof, Fig.5-b. *Kukreti & al (1987)* used the same

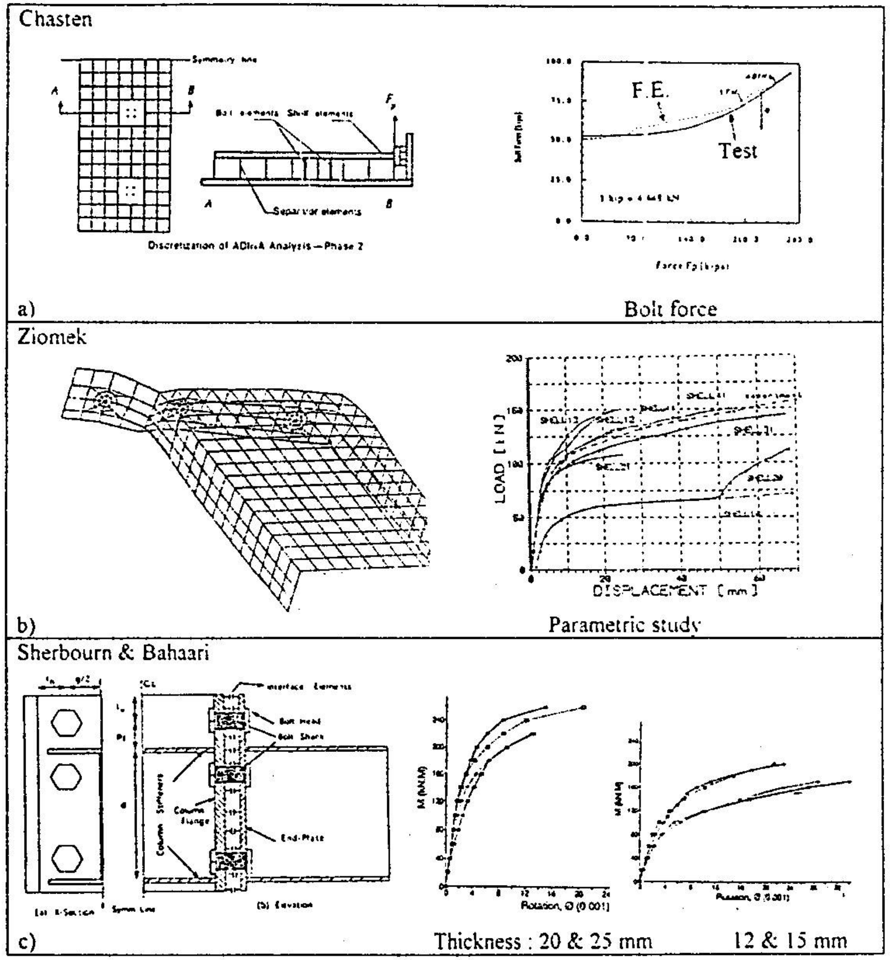

Figure 4- Shell models

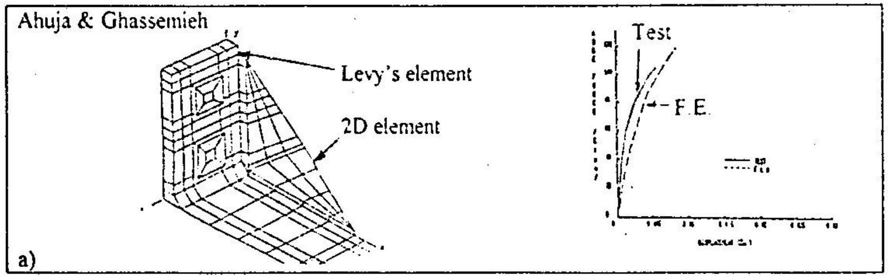

Figure 5- Solid models

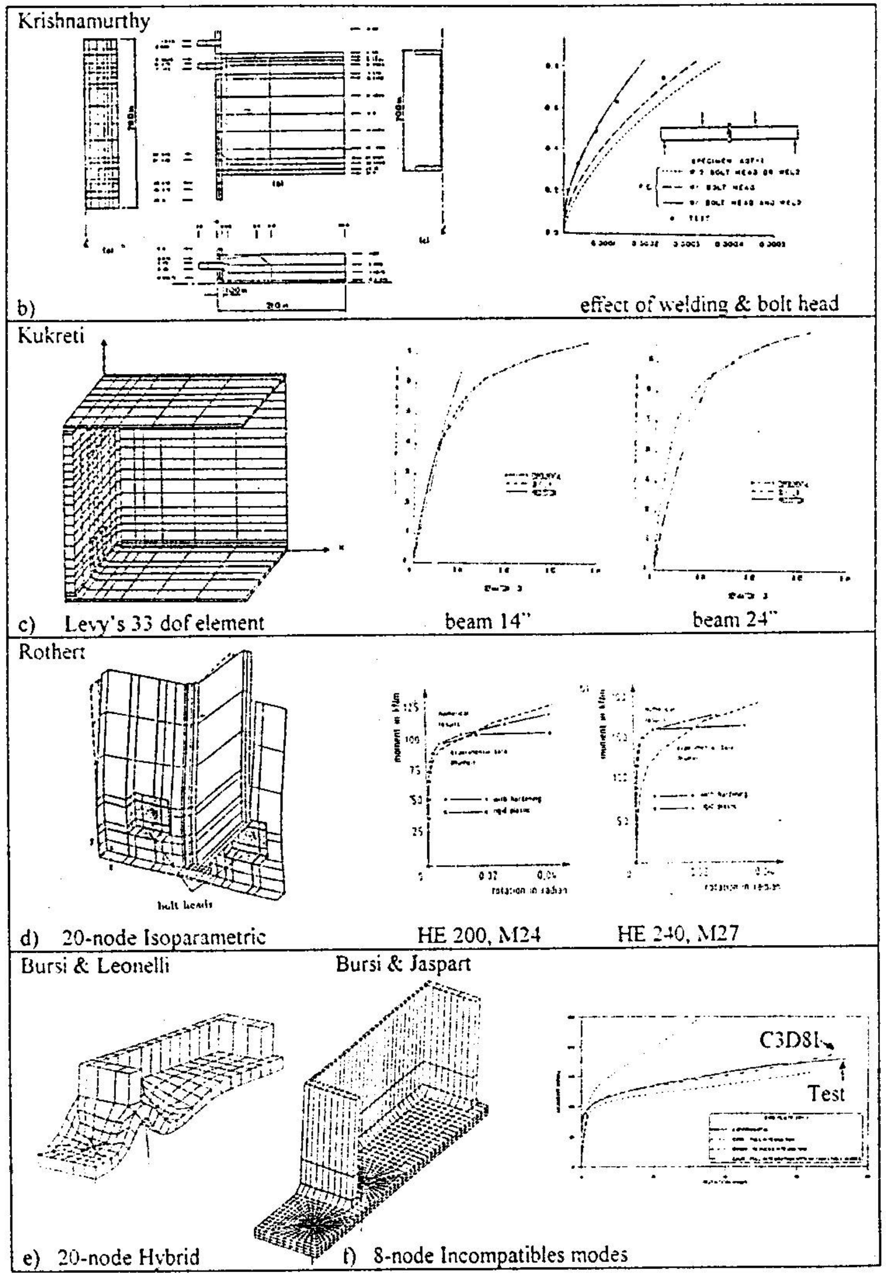

Figure 5- Solid models -Continue

element for flush end-plate joint by improving the material behaviour . In his model an elastic-perfectly plastic material was used. The comparison between experimental and numerical results shows that the errors of measured moment in the maximum applied displacement are between 6% and 30%. The maximum displacement is not too far from the plastic displacement of the joint (Fig.5-c) . In this type of modelling with simplification of bolts, welding, the contact approach, material properties etc... we can not judge about the element.

Rothert & al (1992) tried to model only the column flange . Because of two lines of symmetry, the one eighth of structure (one T-stub) was modelled(Fig.5-d). An isoparametric 20-node element is used . The thickness of end-plate was between 13.7 and 16.4 mm and one layer model was presented. The bolts and shanks are square shapes . The material nonlinearity is incorporated in model but the detail of work hardening rule is not clear. In reality, we can not model one eighth of flange and neglect the important interaction between several T-stubs. This is one of the important source of errors. Furthermore, there is a perfect adhesion between flange and bolt head. The effect and significance of non frictional contact between bolt head and end-plate are shown in 2D model.

Sedlacek & al (1994) during a short report about the research in Germany, proposed a 3D solid F.E. modelling for a single sided joint . Unfortunately the details are not available, The only curve shows the upper and lower boundaries results obtained from input parameter variation which compared with test result.

Bursi & al (1994) proposed an other model for a single side joint . In this model a 20-node hybrid solid element with one layer modelling of 12 and 25 mm thickness is used . The bolts are simplified and the standard two node beam elements to model shank and heads are used. The real beam is neglected and only a small portion of it is modelled . In this simulation, 27 Gauss integration points are used . The results are stronger than reality . For reducing this effect and this reality that non of the gauss points are located at the boundaries of the element (e.g. on the top and bottom surface of the end-plate), and both the yield and ultimate stress scaled to 0.77 of their actual values . With this correction, the result in hardening branch of moment-rotation curve is more softer than experience. In 1995, *Bursi & Jaspart* improved the last model by substituting the element with a 8-node incompatible modes(C3D8I in ABAQUS), and one layer element in thickness with three layers. Furthermore, a part of beam was added to the model. They presented the result for the 12 mm end-plate thickness which agreed with experience (Fig.5-e).

Nemati & Le Houedec (1996) proposed another model based on the SAMCEF code. The element is a 20-node isoparametric solid element with 8 points of Gauss. The most important characteristics of this model are; 1- a three layers mesh for end-plate is used 2- the bolts are modelled with solid element in circular shape, and there is contact between bolt head and end-plate 3- the effect of welding on heated zone which changes the yield point of material is taken into account 4- a bilinear hardening rule is used with actual yield stress. The slope of hardening branch of stress strain curve is equal to 2.5% of Young's modulus. The simulation is made for a joint with 18 mm of end-plate thickness. The results are satisfactory for monotonic loading(Fig.6). The same mesh is used for thin end-plate but the results appears to be softe. However the result with the same mesh but only one layer for thin end-plate and 4% slope for hardening branch of material, is acceptable.

As we mentioned before, the simplified models are not suitable to judge about the capacity of finite elements in inelastic behaviour. Furthermore, it is difficult to justify the use of only one layer element for thick end-plate in inelastic range, the neglect of the beam and modelling only one part of connection and extend the result to a complete joint.

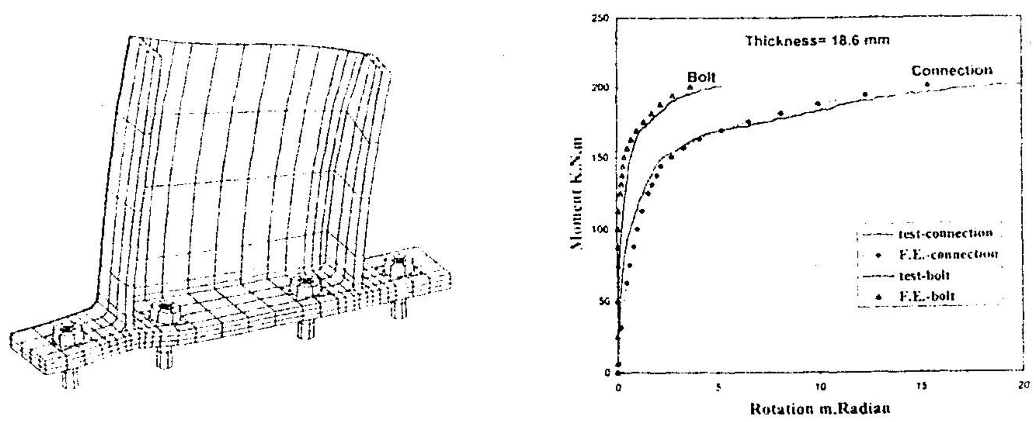

Figure 6- The model of Nemati & Le Houedec

4- Conclusions

With progress of softwares and hardwares in recent years, and today's industrial requirements, we can conclude that :

1- The model of plane stress and plate bending are not sufficient to have a complete understanding about end-plate joints.

2- The shell element model, reached at a good level but is limited to the very thin end-plate connections which are not really industrial. Furthermore the capability of shell element in cyclic loading and using the actual yield stress are in question.

3- The solid element model, seems to be the best solution for the problem, but for evaluating the capability of different solid elements, we need a complete model. The general programmes, allow us to model almost of all mentioned phenomena with minimum simplification. However the library of available elements in some of these codes seems not sufficient.

4- The following requirements are not incorporated in solid models until now :

a- actual loading (applied in the end of beam) b- residual stress c- lack of fit (we need new tests with correctly measured lack of fit) d- introduction of failure mode e- buckling effect which is very important specially in cyclic behaviour.

5- The following requirement are expected from solid F.E. models :

a- the contribution of each phenomena in final results b- parametric study c-cyclic behaviour of end-plate joint

6- the following problems are open to discussion :

a- is it necessary to use one type of element for all type of end-plate thickness ? The authors are convinced that the behaviour of very thin end-plates (however they don't seem industrial) are different comparing with thick ones. In thin connections we have an excessive deformation and all classical elements don't work in this situation.

b- In many models, the input data for material characteristics are artificial, for example:

I- the yield stress is not exactly the measured datum. The nominal or scaled values are used

II- The work hardening is perfect elastic-plastic or an arbitrary slope for a bilinear or trilinear curve is chosen.

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