FEM MODELING WITH MARC OF CRACK PROPAGATION

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SUMMARY: The objective of the development is to add to the MARC program the feature of crack propagation for progressive material failure. The development is in the form of a block of User Subroutines. The material is assumed to fail when a stress measure, chosen by the user among four options, exceeds the corresponding stress limit (set by the user). The Finite Element mesh is torn along an element side; one side at a time. This way the crack propagates all the way up to body failure, or up to a stop.

KEYWORDS: fem, crack, propagation, failure

INTRODUCTION

The Finite Element Method (FEM) discretizes the continoum theory; therefore FEM is inherently uncapable of modeling the breaking apart of the material. On the physical side, the material starts breaking at one point where a high stress concentration occurs. A small crack develops there and, under the effect of the applied forces, the crack may propagate all the way up to breaking apart the body. We have implemented in the MARC Code (MARC Analysis, 1996) a feature of crack propagation that replicates the physical phenomenon by:

- splitting the continuous mesh and generating opposite crack faces;
- redistributing the stresses released by material failure onto the mesh
- configuration produced by the crack extension.

The following simplifying assumptions have been introduced:

- The geometry of the problem is plane. Small strains are assumed.
- Quadrilateral elements are used.
- The applied loads/strains are static. The material fails by overstress (no fatigue effect).
- The failure at any point of the material is identified by a certain stress measure exceeding its associated stress limit;
- The crack propagates only along the edges of the existing elements.

The result of such development is an add-module for the MARC Code in the form of User Subroutines that produces the crack and that follows the crack propagation from start to end. The algorithm for crack propagation stops when the stresses around the crack tip fall below the failure limits; or, alternatively, when the body breaks apart. A number of simple test cases have been investigated.

MATERIAL FAILURE

The failure in the material is associated with a certain stress measure, chosen by the user and indicated by $\underline{\sigma}$, when exceeding its limit value σ_{lim}. It is the case of brittle failure of isotropic materials. The stresses are computed at the Gauss points of the quadrilateral elements around the crack tip. The event of occurred failure and the selection of the direction of crack propagation are detected with a multiple-level logic starting from the value of the stress measure $\underline{\sigma}$ at the Gauss points surrounding the crack tip and from the values of the stresses σ_n and τ, normal and tangential to each element edge. Notice that around the crack tip there are only 3 element edges eligible as direction of crack propagation; the 4.th edge is the crack itself. The MARC user selects which stress measure he wants to use; typically one uses $\underline{\sigma} = \sigma_{vm}$ i.e. the Von Mises stress measure. As alternatives he may choose the tearing stress σ_n or the shearing stress τ along the crack edge.

THE CRACK PROPAGATION ALGORITHM

We outline here the algorithm, implemented as an add-module in MARC, that automatically:

- identifies a point of initial material failure;
- produces an initial crack;
- follows the extension of the crack step-by-step.

The algorithm assumes that :

- The loads/strains are applied step-wise to the component (as load INCREMENTS in MARC).
- The crack propagates only along element edges.

At first that seems a gross limitation; however, the fine meshes currently used for crack propagation and the subsequent remeshing do not impair an accurate prediction of the strain energy released. On the other end, the prediction of the shape of the crack is highly undetermined, even at the experimental level. Crack propagation develops as follows :

1. The crack advances by one element edge at a time; from the start node to the end node of the edge; the stresses released by the crack are redistributed over the remaining elements.
2. The resulting state of stress around the crack tip is checked for further material failure :

- if the material fails, another element edge is cracked open; the algorithm decides which of the element edges around the crack tip must be split. The analysis of the load increment continues iteratively, going back to point 1 above.

- if the material does not fail, the crack stops. The analysis of the load increment is complete. Control is passed back to the MARC nonlinear solver, that applies one more load increments, or stops.

The following further computational details are relevant; they are related to the fine grain of computation:

The algorithm is implemented for 4-noded plane elements.
The crack extends one element at a time; choosing that element where, at a Gauss point, the largest stress measure (i.e. Von Mises: $\underline{\sigma}_{max} = \sigma_{vm}$) exceeds an assigned stress limit for the material (i.e. the yield stress :$\sigma_{lim} = \sigma_y$).
The element edge to be split is chosen by a User Subroutine (ADTEAR), on the basis of certain stress measures at its boundary.

Once the edge is chosen, the two opposite faces of the newly opened crack are identified; the boundary stresses previously applied to them become now a residual force that is gradually leveled to zero, in one or more equilibrium recycles.
The split faces thus extend the boundary of the crack : they become now contact surfaces, and as such they may be assigned a friction coefficient.

Table 1 : Steps of the crack propagation algorithm

1. **Crack initiation**	Identify the element *m* at whose g.p. there occurs : $\underline{\sigma}_{max}>\sigma_{lim}$; Turn on the flag for crack initiation.
2. **Crack direction**	Identify the edge *n* of element *m* to be split.
3. **Crack opening**	Split side *n* of element *m*, producing a new node and thus a new edge for the element. Open the crack by adding two opposite element edges to the contact surfaces; the crack advances by the entire element edge.
4. **Force balance**	The stresses previously applied to both sides of the split element edge, produce residual forces that are to be balanced by equilibrium recycles, within the same load increment.
5. **Crack extension**	Check if at the new crack tip the adjoining elements have $\underline{\sigma}_{max}>\sigma_{lim}$ at any g.p; if so the crack extends. Repeat the steps 2, 3, 4, 5 above.
6.	When the crack stops propagating, the increment is terminated. MARC turns control to the next increment.

After the equilibrium recycle has balanced the residual internal forces, the algorithm move to the next load increment. Now the two elements adjoining the new crack tip are checked for overstress; if either element is overstressed, the crack will be further extended by one element edge. When the global force equilibrium is achieved within the same increment, and when no overstress is registered near the current crack tip, the increment is completed. The algorithm is illustrated at the qualitative level in Tab. 1 and in Fig. 1. Fig. 2 shows the evolution of the crack in a MARC run where a simple plate under traction is torn apart.

CONTACT ALONG THE CRACK

In many physically relevant circumstances, the opening of the crack does not prevent the two opposite faces from exerting mutual forces. For instance, if the crack is open by shear, a normal force may still be exerted between the two faces, and, because of friction, a tangential force may arise. Thus, when the cracks open, the algorithm automatically "registers" that the split sides of the crack become contact surfaces of two flexible bodies in contact; the contact surfaces extend themselves with the propagation of the crack. The MARC user may assign friction to be present at the contact surfaces, and thus during crack propagation the two opposite faces of the crack may exchange a normal as well as a tangential force. When the crack propagates along a direction that is oblique with respect to the gridlines of the mesh, the open crack will show a "seesaw" profile. In the case of active contact between the crack surfaces, the seesaw profile would lock any sliding between the contact surfaces. To prevent such an effect, that would alter the mechanics of crack propagation, a "crack-stretching" feature is being developed as an algorithm that straightens the seesaw profiles into straight lines. The mesh is rezoned in the crack area, to recompute a consistent state of stress.

CONCLUSION

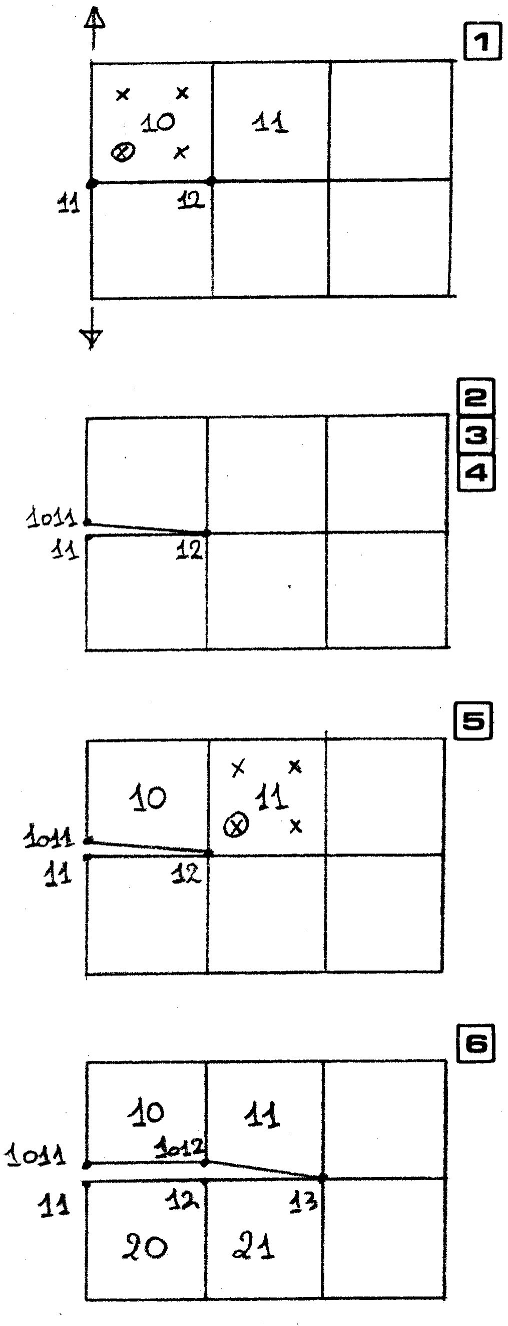
The cracking open of the continuous material is novel to the commercial FEM codes. It is not simple either, as it takes:

- identifying were and how the material cracks;
- doubling the mesh along the crack sides;
- applying contact/friction boundary conditions along the newly formed boundary of the crack.

The development presented here is just the first step in that direction. Work is in progress.

REFERENCES

MARC Analysis, 1996 "user Manuals, Volumes A, B, C, D"



1. identify element 10 where $\underline{\sigma}_{max} > \sigma_{lim}$ at some g.p.; find the closest node to g.p. (i.e. node 11);

2. identify the element edge to be split (i.e. 11-12) from the criterion chosen for crack direction;

3. split the edge at node 11, producing the new node 1011;

4. rebalance the forces released by crack propagation;

5. repeat step 1 above for element 11, where now $\underline{\sigma}_{max} > \sigma_{lim}$;
The crack propagates to the next edge, i.e. : 12-13.
Contact is established, internally by MARC, between a new flexible body 1 (el 20) and a new flexible body 2 (el. 10).

6. These contact bodies grow automatically by new elements edges whenever the crack propagates.

Fig. 1 : Qualitative 2D-example of crack propagation

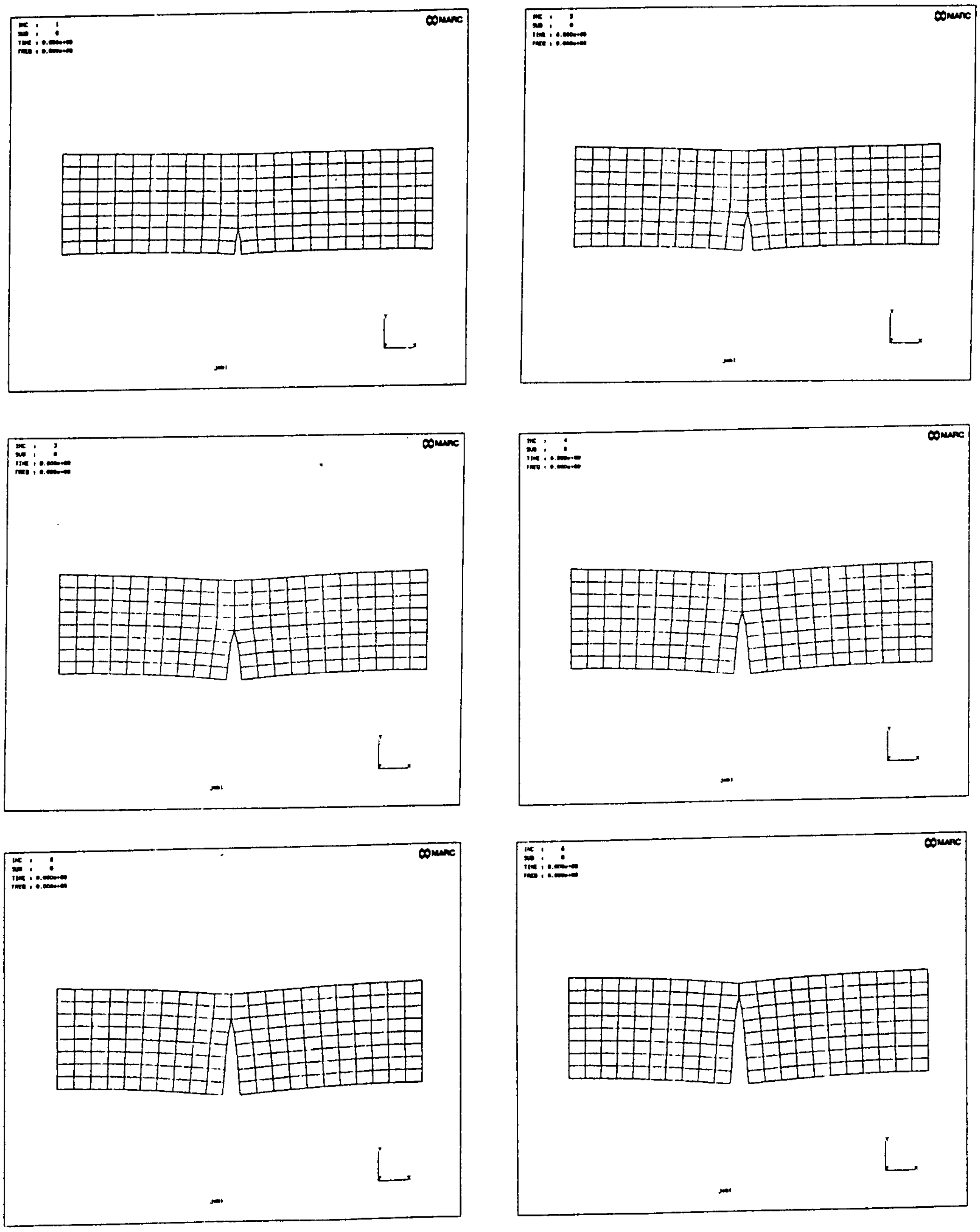


Fig. 2 : Evolution of crack propagation during the recycle at inc. 1