# DE–FE method for simulation of the behaviour of furniture during earthquake

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## 1. Introduction

The collapse of heavy furniture is one of the critical factors affecting human safety during earthquake. The numerical study of this phenomenon is most conveniently done by rigid body representation, whereas a piece of furniture is represented by a single lumped mass and rotary inertia. The geometrical shape is described in terms of a set of planes attached and moving together with the rigid body, e.g. [1]. During the solution, a search for possible contacts is done, and then the contacts are resolved, producing contact forces that drive the rigid body into motion. The rigid body representation is a fast and relatively simple method which can be used with confidence if the furniture simulated is rigid enough, and is not expected to break into pieces during the earthquake, e.g. refrigerators, washing machines, ovens, etc.

On the other hand, there are types of furniture for which the rigid body representation may not be adequate, e.g. more flexible furniture made by sheet material, like book shelves, cupboards, etc. It is for this type of furniture that the proposed method is intended. In it, the furniture is modeled by finite elements for better accuracy in the overall behaviour, as well as for checking of the deformation and integrity of the piece of furniture itself, impossible by the rigid body method.

## 2. Method of analysis

The furniture to be analysed is meshed into finite elements. The structural mass is lumped to nodal mass and rotary inertia. Consistent as well as “engineering” lumping schemes may be used. The nodes also act as contact interfaces by which the piece of furniture interacts with the surrounding walls and the floor. To this end, a node is considered to be a sphere with a small radius, so the contact problem becomes a simple one between a sphere and a plane, often encountered in the DEM. The damping and stiffness during contact have to be specified as input data, preferably obtained by experiment. An explicit time-stepping dynamic relaxation algorithm is used, whereby the procedures carried out during one time step are as follows:

- Update the global coordinates of the unit vectors of the local coordinate system
- For each finite element, transform its nodal displacements from the global to the local coordinate system.
- Then compute the nodal force increments due to each element in the local coordinate system, and add them to the existing nodal forces
- Finally, transform each nodal force to the global coordinate system and sum-up nodal force contributions for each node.
- After nodal forces are assembled, the accelerations, velocities and the new displacements of the nodes are computed giving the data needed for the next time step.

At the beginning of an analysis the only external force acting on the model is the force of gravity. Collision and friction forces due to contact with the boundary planes (floor, ceiling and walls) together with gravity, control the dynamic behaviour of the model. The input earthquake motion is specified as prescribed motion of the boundary planes, which move together as if attached to a rigid body. In principle, material nonlinearity may be included, as well as breaking up of the model into patches of elements, following failure. Damping within the model is considered as Rayleigh type. Global matrices are not used; all computations are done on single element level.

## 3. Implementation and verification

The particular implementation uses 3-node, triangular shell elements, made-up of a membrane [2] and a plate component [3]. Both the membrane and the plate are derived by the ANDES method, and together contain all 6 physical DOF per

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node (3 rotations and 3 translations). This element was chosen for its simplicity (only corner nodes, and physical degrees of freedom), implying fast computation, and its high accuracy even for very high aspect ratios. 3-d frame elements may be used together with the shells. A model including a part modelled by a rigid body and a part modelled by finite elements is also possible.

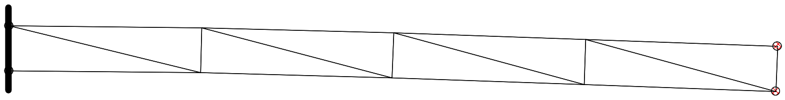

**Fig. 1** Meshing of the cantilever used for verification (deformed shape)

To verify the performance of the shell finite elements, and the solution by dynamic relaxation, the model of a cantilever shown in Fig.1 was used. It is 16m long, with Young's modulus $E = 2.1\text{x}10^6$ kN/m$^2$, and a cross section of 1.0m/1.0m.

The model was loaded by two forces of 0.5kN at the two nodes at the tip; first in-plane, and then out-of-plane of the shell elements. The expected theoretical displacement at the tip is 7.80x10$^{-3}$ m, while the computed displacements for the in-plane and out-of-plane conditions were 8.0x10$^{-3}$ m and 7.74x10$^{-3}$ m respectively. The accuracy is very good considering the coarse mesh used in the verification. Next, an actual furniture collapse simulation is performed. The input motion with all three components applied simultaneously is shown in Fig. 2. The simulated shelf is made of soft wood, with wall thickness 0.20m, and dimensions 0.8m/0.4m/2.1m. After several collisions with the walls, the shelf flips over and then slips on the floor several times. Four frames during the run time are shown in Fig.3.

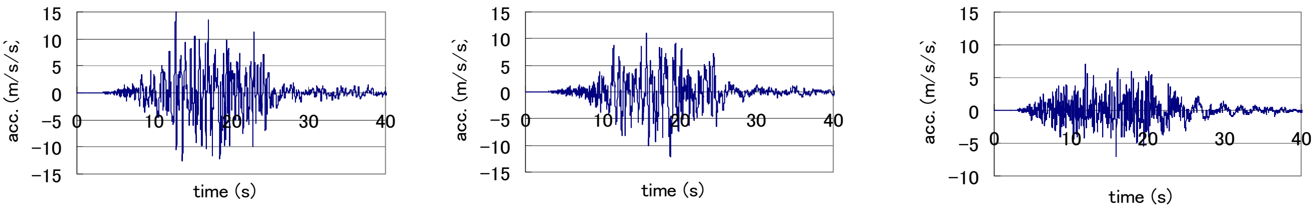


**Fig. 2** The input motion; from left to right; N-S, E-W, U-D components

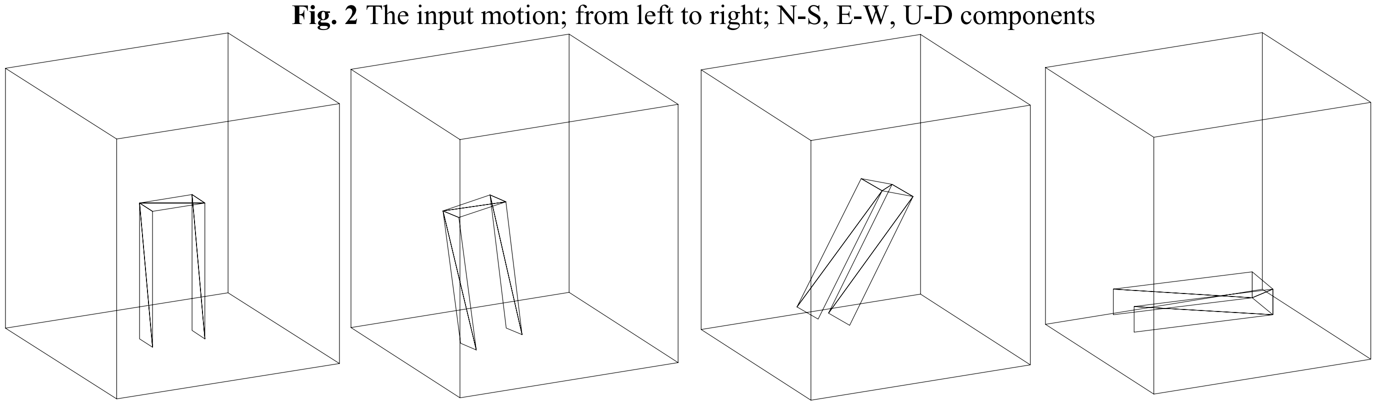

**Fig. 3** Collapse process: from left to right; shapes at 0 s, 10 s, 13 s, and 20 s

## 4. Conclusions

A hybrid DE-FE for collapse analysis of furniture was formulated, its accuracy tested, and its ability to simulate the behavior of furniture during earthquake demonstrated.

The use of high-performance finite elements allows the accurate modeling of the stress-strain state in the furniture at any time, allowing a more accurate estimate of the response at collision to be made; wave propagation in the model is considered. At the same time, the DE algorithm allows to solution to be done without assembling a stiffness matrix, and the contact problem is easily handled. Special provisions need not be made for geometrical nonlinearity either.

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