ENERGY ABSORPTION OF THIN WALLED STRUCTURE WITH EXTERNAL STIFFENERS SUBJECTED TO AXIAL CRUSH

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Experimental and numerical studies of ribs reinforced extruded aluminum column subjected to axial crush were carried out and results were compared with that of empty column. The outcomes of numerical study were found to be in good agreement with the experimental results with the variations of 5–8%. Analysis has been carried out to study the effect of crushing rates and material nonlinearities on the crush characteristics. Results show that distance between the ribs plays a vital role in modifying the energy absorption capacity of structure by 50% with reduction in initial peak force by almost 5–7% as compared to empty extruded aluminum column for a given crushing distance.

Keywords: Crush test, Initial peak force, Energy absorption, Extruded aluminum column, Rib reinforcement.

1. INTRODUCTION

Car safety becomes the most critical issue that has to be taken into consideration while designing the automobile structure. In general, injury in automobile crushes can be considered to arise from four distinct sources: (1) excessive acceleration forces (2) direct contact of passengers with injurious surfaces (3) excessive repulsive peak force (4) adequacy of energy attenuation systems.

Thin walled extruded aluminum structures have been widely used as energy absorbers in crashworthiness applications like automobile and aerospace industries due to its high strength to weight ratio, ductility and recyclability. The structural integrity of the vehicles is now more than ever, a critical design element considering the new light weight materials such as aluminum, composites are being used to build the vehicles. Thus it is essential to assess the crashworthiness of these light weight materials.

Axial crushing of thin wall structure form a major part of the energy absorbing processes. In order to alter the energy absorption during axial crush, an axial compression of a rib reinforced thin walled cylinder structure has been investigated experimentally and theoretically by T. Adachi et.al [1]. They prescribed that a thin wall cylinder with stiff ribs can be used as a structural element to enhance the energy absorption characteristics. In the same way, structures of various forms like tapered tubes (frusta) [2] and grooved tubes [3], have been canvassed by researchers. Z. Zhang *et al*. [4] studied the bending behaviour of a rib-reinforced thin-walled hollow tube-like beam. They studied the effects of the shape of the reinforced rib and also prescribed the shape optimization techniques for enhancing energy absorption capacity of the structure.

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While the use of the external ribbing improves the energy absorption capacities, detailed investigation of the crush characteristics at different rates of loading is not fully understood. Further, the placement of ribs around the column considering the fundamentals of dynamic crushing of the column is not explained in detail. The existing literature does not provide insight of improving energy absorption capacity of this structure while reducing the severity of collisions. The severity of accidents and injuries are dependent on the magnitude of repulsive peak forces resulting from crushing phenomenon. These repulsive forces which result from application of an acceleration are related to strength and stiffness of the structural. In this aspect the structure can be designed which can distribute the forces evenly and absorb as much as energy through progressive buckling.

2. COMPUTATIONAL METHODOLOGY

2.1. Geometry and Support Condition of Structure

The commercially available extruded square section tubes made of aluminum material were used in this study having inner dimension of 23.4 × 23.4 mm, 2 mm thick as shown in Figure 1. The length of tube was selected as 150mm, so that it can capture the desired folding mechanism without influenced by contact nonlinearities effects. This thickness selected for tube because it is typical for aluminum automotive structures. In the case of rib reinforced column, the aluminum ribs having a thickness and width of 2 mm and 5 mm respectively were fabricated and TIG welded around the aluminum column. But the placement of ribs around the column is vital from enhancing the energy absorption ability. It was found out that most favorable distance between the ribs should be 2/3rd that basic collapse element for empty box column. The plastic collapse element length for the square geometrical section considers here is approximately equal to 20 mm [5]. Hence the 2/3rd of that is equal is 15 mm. For any other distance between the ribs other than 15 mm will lead to bending or irregular buckling of the structure which is not the efficient mode of energy absorption

2.2. Details of the Finite Element Model

2.2.1. Details of the mesh

The finite element models as shown in Figure 2 were developed here to study the collapse behaviour of the structure subjected to axial crushing using a non linear explicit solver LS-DYNA®. The axial crushing analysis was performed for the rates of 5 and 6000 mm/min with a maximum deformation

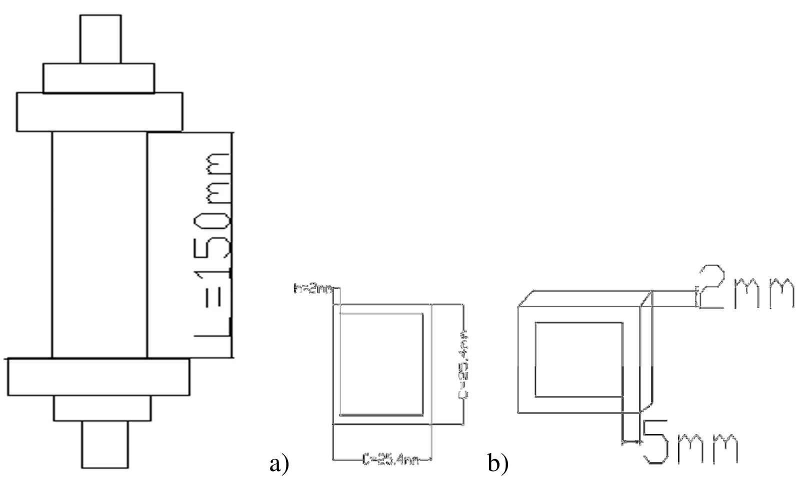


Figure 1. Geometry and support condition of structure. a) Empty extruded aluminum cross section. b) Rib geometry.

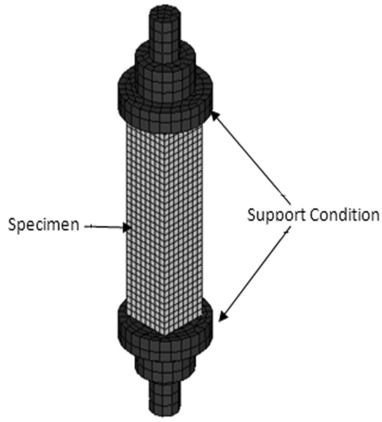


Figure 2. Three-dimensional finite element model.

length of 50 mm. In numerical analysis, the extruded aluminium column and ribs made of extruded aluminium were modelled using Belytschko-Tsay 4-node quadrilateral thin shell [6] element of size 3 $\times$ 3mm with four integration points through the thickness and single point in the plane of the elements. In the case of rib reinforced column the TIG weld was modelled as a rigid spot weld. The yield strength of the TIG welding is higher than the base metal [7]. Thus failure of TIG welding was not considered in the numerical analysis. The loading plate was modelled as a rigid wall using brick elements.

2.2.2. Boundary conditions and contact conditions

The specimen was held between the two rigid platens. The both ends of specimen were free. The nodes of the bottom and upper surface of the column were free in the crush direction. The velocity was given to rigid block wall, which in turn applied at the lower end of the specimens. *BOUNDARY_ PRESCRIBED_MOTION_RIGID (LS-DYNA keyword user's manual) was defined to displace a platen at a constant loading rates of 5 and 6000 mm/min. In order to prevent the tube from drifting on the top end, flat rigid surface was defined above the tube. This was done by employing *RIGIDWALL_GEOMETRIC_FLAT command in LS-DYNA. Node to surface contact with a friction coefficient of 0.2 to avoid lateral movements of the specimen was used between the impact surface of the column and the rigid wall. In order to account for the contact between the lobes during deformation, a single surface contact algorithm without friction was used. The Surface to surface contact was considered for the contact between the ribs and column during deformation of rib reinforced columns.

2.2.3. Constitutive modelling of materials

2.2.3.1. Extruded aluminium column

The extruded aluminum material was modelled as an elastic-plastic material model. The effective plastic stress-strain characteristic for an extruded aluminum under uniaxial loading was obtained from tensile tests, carried out on MTS machine for strain rate ranging between 10^{-3} to 1 $\sec^{-1}$ approximately. The material used in the study was extruded aluminium tube of yield strength (σ_y) $=$ 152.96 MPa, Young's modulus (E) =69.5 GPa, Poisson ratio (μ) $= 0.3$ and density (ρ_{Al}) =2700 kg/m^3. By analyzing extruded aluminum stress-strain characteristics, one can conclude that yield stress is a function of strain rate, so material model that takes into consideration the strain rate hardening effect was used in the numerical analysis. Thus MAT_3 PLASTIC_KINEMATIC material model incorporates kinematic hardening including strain rate hardening effect was used to define the aluminium extrusion structure in finite element modelling. Rate effects in this material model are taken into consideration by Cowper-Symonds constitutive equation. The uniaxial true stress-strain characteristics of the material obtained at different strain rates were used to calculate the Cowper-Symonds material parameter.

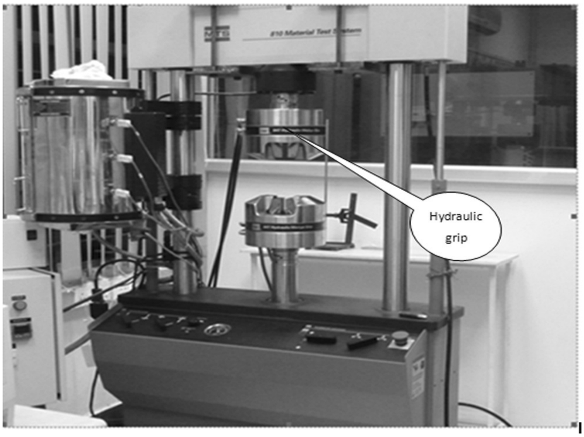


Figure 3. Material test System.

3. EXPERIMENTAL INVESTIGATION

3.1. Material Test System

Crush tests was performed using a servo hydraulic MTS machine a shown in Figure 3. The test system comprises of a load frame fitted with a servo-hydraulic actuator, load cell, a servo-valve assembly, a computer controlled data acquisition system and test sequence programmer. The displacement is measured from LVDT fitted above the upper hydraulic actuator.

3.2. Axial Crush Tests of Columns

Axial crush tests were conducted on the empty and rib reinforced box column for 5 and 6000 mm/min rates. The fixture designed for holding structural elements is as shown in Figure 4**.** These are the two rigid platens which can be grip into the hydraulic jaws of the MTS machine. The specimen was held between these two platens.

Figure 4. Tube holding Fixture.

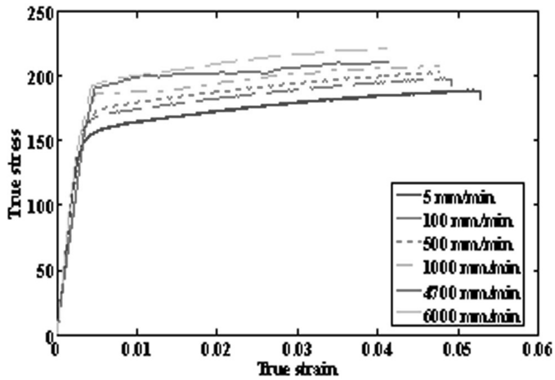


Figure 5. True Stress vs. True strain curve of aluminium used in the Study.

3.3. Mechanical Testing of Specimens

3.3.1. Dynamic stress-strain relations for metals

Room-temperature tensile tests were conducted on the tensile test specimen manufactured according to ASTM (E8) standards. Results of the tensile tests are shown in Figure 5. Due to the non-linear stress-strain characteristics of extruded aluminium, a proper description of the hardening properties of the material is essential. In the numerical study, Cowper Symonds equation was used which take into consideration the effect of strain rate hardening.

COWPER SYMOND EQUATION

$$\varepsilon = D\left(\frac{\sigma_d^\circ}{\sigma} - 1\right)^{\frac{1}{q}} ; \sigma_d^0 \geq \sigma \tag{1}$$

As shown in Figure 6, the above equation is of straight line with log (σ_d^0/σ-1) plotted against log $\dot{\varepsilon}$ at different strain rates. The parameter "q" is the slope of straight line while intercept on ordinate is the “log D”. Therefore $q = 3.035$ and $D = e^{4.150} = 63.4340$.

The mechanical properties of TIG welded ribs are similar to those obtained for the thin wall aluminium column.

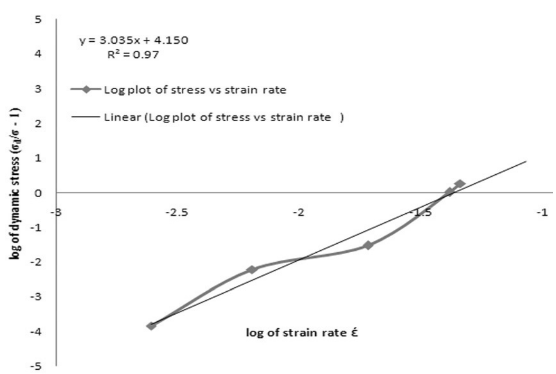


Figure 6. Log plot of stress vs. strain rate.

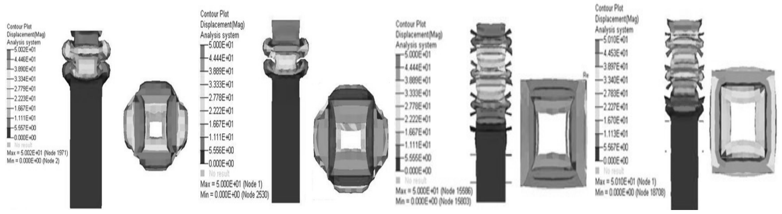


Figure 7. Finite element model of deformed empty and rib reinforced specimens subjected to axial crushing at four different rates. a) Velocity = 5mm/min b) Velocity = 6000mm/min c) Velocity = 5mm/min d) Velocity = 6000mm/min

4. RESULTS AND DISCUSSION

4.1. Empty square box columns

Figures 7a and b show the collapse behaviour of the empty box square column for two different crushing rates. It depicts the following features

(i) A stable progressive symmetric folding collapse from the upper face of the column. (ii) The formation of a total of two folds for the deformation length of 50mm. The force-displacement and energy-displacement characteristics are shown in Figures 8 and 9.

4.2. Crush behaviour of rib reinforced column

Figures 7c and d show the collapse behaviour of the rib reinforced box square column for two different rates. The results show that (i) The stable progressive symmetric and extensional (mixed) deformation mode start from the upper face of the column and the formation of a total of three folds for the crushing length of 50mm. (ii) The reduction in the plastic fold length and initial peak force by 5–7% compared to empty column for the same crushing distance. (iii) The energy absorption capacity of the structure is 50% more than the empty box column. The corresponding force-displacement and energy-displacement characteristics are shown in Figures 8 and 9 respectively.

The crush characteristics obtained from numerical analysis are enumerated in Table 1.1. The terms in bracket indicates the percentage change in the quantity when compared to empty box structure.

The following general observations were made by analyzing the outcomes of the crushing phenomenon:

Force-displacement curves were characterized by a high initial peak force followed by oscillations and this implies that compressive repulsive force is higher when the first hinge was formed, but that

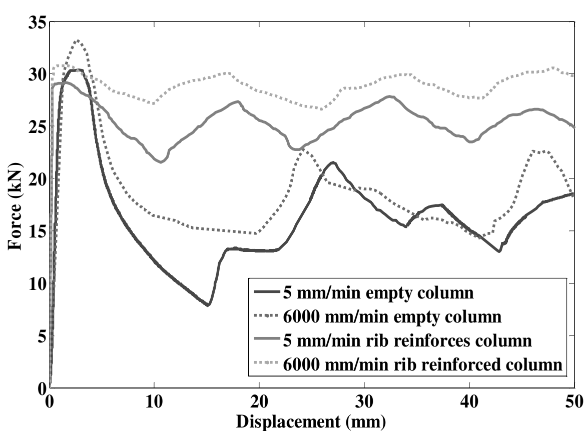


Figure 8. Force vs. displacement curves for empty and rib reinforced box column for two different rates.

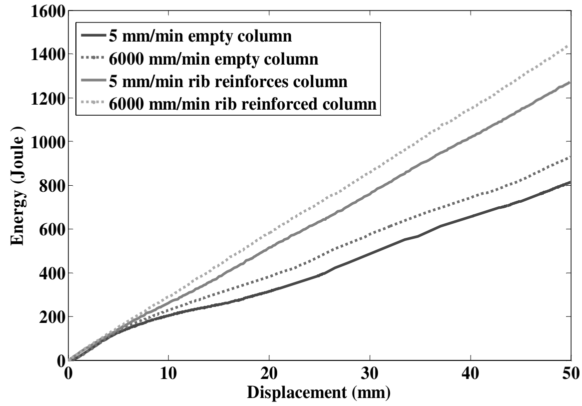


Figure 9. Energy vs. displacement curves for empty and rib reinforced box column for two different rates.

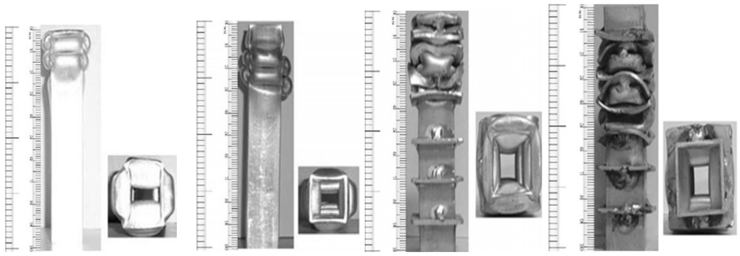
Table 1. Crush characteristics obtained from experimental tests at different Loading rates.

Sr. No.	Rate Of Loading (mm/min)	Peak (Numerical) Force(KN)		Energy absorbed (Joule) (Numerical)		Peak Force(KN) (Experimental)		Energy absorbed (Joule) (Experimental)	
		Rib reinforced Column	empty column	Rib reinforced Column	empty column	Rib reinforced Column	empty column	Rib reinforced Column	empty column
1	5	29.1 (−3.32%)	30.1	1270.96 (56%)	814.89	28.8 (−4%)	30.01	1233.5 (52%)	809.7
2	100	29.4 (−4%)	30.6	1322.24 (54.6%)	855.01	29.2 (−3.3%)	30.18	1302 (54.2%)	844.2
3	1000	29.8 (−5%)	31.18	1371.97 (50%)	914.23	29.5 (−2.4%)	30.2	1359 (54%)	882.9
4	6000	30.8 (−7.5%)	33.3	1437 (54.7%)	928.95	30.6 (−6)	32.5	1434 (57.5%)	910.1

ensuing hinges were formed under smaller repulsive force. The wobbling behaviour in the force-displacement curve during axial compression of a tube is associated with the formation of the plastic folds. Berstad *et al*. [8] have shown that this behaviour can be co-related with loading and unloading of the material and that the rate hardening properties of material may be crucial for modifying energy absorption.

In the case of rib reinforced structure, the ribs placed around the column forced the supporting wall of the column to collapse in a given constrained space with mixed deformation mode, accompanied by the reduction in the fold length. Reduction in folding element length for the same crushing distance assist in generating more number of plastic hinges with increase in the mean crush force. The energy absorption depends upon the formation of as many as plastic hinges. This results in a 50% increase in energy absorption capacity (Figure 9) and reduction in initial peak force up to 7% (Figure 8) as compared empty extruded tube. This argument suggests that rib spacing plays a vital role in adjusting or modifying the energy absorption capacity of the structure.

The results reveal that the impact velocity has a significant influence on the mean crush load of the tube. It was found out that the mean crush load and energy absorption capacity increased with an increase in rate of crushing. This increase in crush load must be attributed to material strain-rate sensitivity.



(a)Velocity=5mm/min (b) Velocity=6000mm/min c) Velocity=5mm/min (d) Velocity=6000mm/min

Figure 10. Collapse behaviour of empty and rib reinforced aluminum specimens obtained from experimental investigation when subjected to axial crushing at two different rates. (a) Velocity = 5mm/min (b) Velocity = 6000mm/min (c) Velocity = 5mm/min (d) Velocity = 6000mm/min

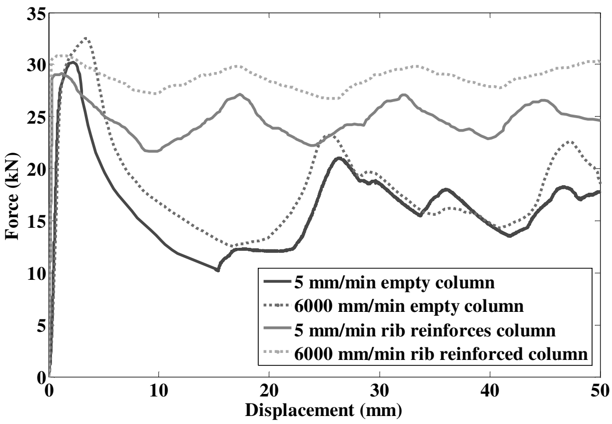


Figure 11. Force vs. displacement curves for empty and rib reinforced box column for two different rates.

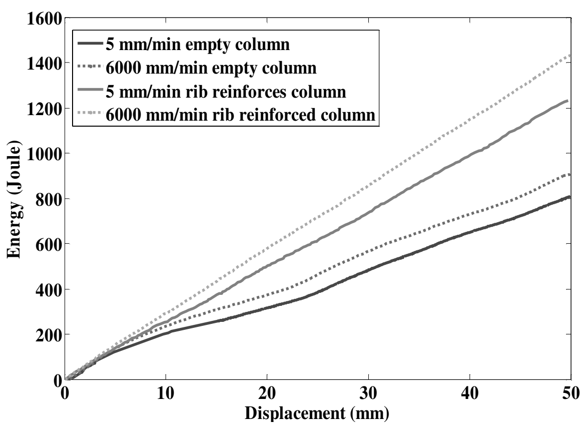


Figure 12. Energy vs. displacement curves for empty and rib reinforced box column for two different rates.

4.3. Comparison Between Numerical Predictions and Experimental Crush Tests

Figure 10a and b show outcomes of the experimental investigation for the empty box columns. Empty column deformed in a symmetric mode with the formation of two plastic folds. The force-displacement and energy vs. displacement response is depicted in Figures 11 and 12 show good agreement with the results obtained from numerical analysis. The crush characteristics obtained from the experiment are on the lower side than that obtained from finite element analysis. This may caused due to geometric imperfection in the material.

Figure 10c and d indicates the collapse behaviour of rib reinforced column subjected to axial crush at different rates. The deformation mode during crushing was found to be combination of symmetric and extensional. The force-displacement and energy vs. displacement characteristics obtained from experiments are shown in Figures 11 and 12. As the strain rate increases, the deformation behaves non-uniformly due to the instability effects. Under the high strain rate, the size of peaks and the distance between peaks on the force-displacement curve tends to be non-uniform. Analyzing the deformation profiles as shown in Figure 10, a small crinkle formed on the tube along its length for the high loading rates. This phenomenon is known dynamic buckling. Table 1 lists the, initial peak force and the absorbed energy obtained from crush tests.

5. CONCLUSION

- The numerical and the compressive tests results were in good agreement in terms of crush characteristics with the variation of just 5%. Thus, the Computational techniques can be effectively used to estimate crush characteristics before conducting the experiments.
- Rib reinforced structures assist in formation of more number of plastic hinges for the same crushing distance as compared to empty box column. This results in the increase in the mean crushing force and energy absorption capacity but with reduction in the folding length and initial peak force. As the initial peak force has a direct bearing on biomechanical loading of the vehicle occupants, reduction in the initial collapse is very much important from the point of view of preventing occupant's injuries.

REFERENCES

1. T. Adachi *et al.* (2008) Energy absorption of a thin-walled cylinder with ribs subjected to axial impact, International Journal of Impact Engineering, 35(2), 65–79.
2. A.G Mamalis, E.D Manolakos, S Saigal, G.I Viegelahn, W. Johnson. Extensional plastic collapse of thin-walled frusta as energy absorbers; International journal of mechanical sciences 28, 1986, 219–29.
3. AG Mamalis, G.L.Viegelahn, D.E.Manolakos, W Johnson. Experimental investigation into the plastic collapse of steel thin-walled grooved tubes; International journal of impact engineering 4, 1986, 117–26.
4. Z. Zhang Design optimization of cross-sectional configuration of rib-reinforced thin-walled beam; Journal of Thin-walled structures February 2009.
5. Wierzbicki T and Abramowicz W On the crushing mechanics of thin-walled structures, *Journal of* Applied Mechanics, 50, 1983, 727-739.
6. LS-DYNA keyword user's manual, (1996) V970, LSTC, Livermore, CA, 2005.
7. Juan Zhao *et al*. Comparative investigation of tungsten inert gas and friction stir welding characteristics of Al–Mg–Sc alloy plates, Journal of Materials and Design,31(1), 2009, 306- 311
8. Berstad T, Langseth M and Hopperstad O.S Crashworthiness of thin-walled aluminum extrusions. 4th International conference on computational plasticity, Barcelona, Spain 3-6 April, 1995