Finite element modelling of the static axial compression and impact testing of square CFRP tubes in LS-DYNA3D

Author:
Dimitrios Papapostolou
National Technical University of Athens

Correspondence:
34 Naiadon Str, P.Faliro, Athens 17561, Greece
Tel.: +30 6973 937 703
Fax: +30 210 98 85 002
Email: dpapapostolou@yahoo.com

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ABSTRACT

LS-DYNA3D finite element code was used for investigating the compressive properties and crushing response of square FRP (Fibre Reinforced Plastic) tubes subjected to static axial compression and impact testing. Several models were created in order to simulate a series of static and dynamic compressive tests that were performed in the National Technical University of Athens (NTUA) using carbon FRP tubes, that were featured by the same material combination (woven fabric in thermosetting epoxy resin) and external cross-section dimensions but different length, wall thickness, laminate stacking sequence and fibre volume content. Modelling the three modes of collapse observed during the experimental works (i.e. progressive end-crushing with tube wall laminate splaying, local tube wall buckling and mid-length unstable crushing) was the primary goal of the simulation works. The agreement between calculations and test results regarding the main crushing characteristics of the tested CFRP tubes –such as peak compressive load and crash energy absorption– and the overall crushing response of the tubes was quite satisfactory as the finite element models were refined several times in order to achieve optimum results.

INTRODUCTION

The use of composite collapsible energy absorbers is getting wider in automotive and aerospace applications nowadays, since they provide significant functional and economic benefits such as enhanced strength and durability, weight reduction and lower fuel consumption [1-2]. In addition they have been found to ensure enhanced level of structural crashworthiness, being capable of collapsing progressively in a controlled manner that ensures high crash energy absorption in the event of a sudden collision. On the contrary to the response of metals and polymers however, progressive crushing of composite collapsible energy absorbers is dominated by extensive micro-cracking development instead of plastic deformation [3-7]. Among the various types of composite structures and materials that have been tried by researchers aiming to achieve improved level of crashworthiness, carbon fibre reinforced plastics have proven to be exceptionally efficient crash energy absorbing components featured by excellent stiffness to weight ratio [3-4].

The simulation works described herein contribute to the investigation of the crushing characteristics of thin-walled CFRP tubular components, by modelling the response of square tubes subjected to static and dynamic axial compressive loading, using the LS-DYNA3D finite element code. The models developed for this work are featured by the geometric and material characteristics of square CFRP tubes used in a series of compressive tests performed in NTUA. Comparison of the computed compressive response to the results and findings of the experimental works detailed in the referenced publications [8] and [9], shows that the finite element models described here, approached the actual crushing response of the square CFRP tubes to a satisfactory degree both in terms of collapse modes and main crushing characteristics such as peak compressive load and absorbed crash energy.

MODELLING DETAILS

Finite element investigation of the crushing response of square CFRP tubes in axial compressive loading started with developing a series of three models corresponding to the three characteristic collapse modes recorded in the course of static tests [8]. Following this initial step, simulation works proceeded with the modelling of the impact testing by preparing a representative model corresponding to the only one mode of collapse observed in the series of dynamic tests [9]. In the following paragraphs, simulation works are described in detail, after a brief presentation of the series of the modelled experimental works which are described in detail and extensively analysed in the referenced works [8] and [9].

Description of the modelled experimental works

The basic geometric and material data of the CFRP tubes used in the models described herein are given in Tables 1 and 2 that follow.

Table 1. Geometric and material data of the modelled square tubes

Test specimen ID	Number of plies	Fibre volume content	Length	Aspect ratio	Thickness	Specimen Mass
	n	V_f	*L*	*(L/w)*	*t*	*m*
(-)	(-)	(%)	(mm)	(-)	(mm)	(g)
Static axial compression tests						
AC-CT1-C-01	10	46,3	119,2	1,12	2,60	166
AC-CT2-B-01	14	48,7	101,6	0,94	3,40	199
AC-CT2-C-01	14	48,7	121,2	1,12	3,40	237
Impact tests						
DT-CT3-A-01	18	50,1	50,4	0,46	4,33	117

Table 2. Basic material properties of the tube wall laminate plies.

Material property	Symbol	Property Value	Unit
Density		1549	kg/m^3
Elasticity modulus in longitudinal direction	E_a	19900	Mpa
Elasticity modulus in transverse direction	E_b	20020	Mpa
Shear Modulus	G_{ab}	3700	Mpa
Poisson ratio between (a) and (b) directions	v_{ab}	0.048	(-)
Poisson ratio between (b) and (a) directions	$v_{b\alpha}$	0.042	(-)

Three distinct modes of brittle collapse were observed in the series of static and dynamic tests. Euler overall column buckling or progressive folding with hinge formation, which according to Hull classification [3] constitute the other two general modes of collapse of FRP tubes, were not observed.

- *Mode I,* is characterised by *progressive end-crushing with laminate splaying* of the tube, starting at one end of the tested specimen, the formation of two continuous fronds that spread outwards and inwards and high absorption of deformation energy. This collapse mode -which corresponds to “splaying” or “lamina bending” type of brittle fracture in accordance with the classification made by Hull [3] and Farley & Jones [4] respectively- was observed only in the case of static tests.
- *Mode II,* is dominated by unstable *local tube wall buckling* on all four sides at one end of the tested tube, and circumferential brittle failure. Local tube wall buckling mode occurred only in the case of static compression of thinner tubes.
- *Mode III*, *mid-length collapse* is featured by brittle fracture and unstable collapse of the compressed tube, which commences with a circumferential fracture of the composite material at a local non-uniformity in the middle of the tube. Crash energy absorption of this mode was very low, but despite that, mid-length collapse was observed in the majority of the static and dynamic tests (78% occurrence frequency).

Finite element models description

Each of the models generated in LS-DYNA3D for the simulation of axial compression tests consisted of three main parts corresponding to the test specimen and the two heads of the press or the drop-weight test machine respectively. In both static and dynamic tests the lower head of the testing machine was a stationary rigid surface, while the upper head was a moving rigid surface with constant velocity in the case of static tests or decelerated after the impact in the case of the dynamic tests. Modelling of these two heads in LS-DYNA3D was made by appropriate types of "rigidwall" interfaces between the interacting parts. Regarding the modelling of movement of the upper crosshead in the case of the static tests a much higher constant speed was used instead of the actual speed of 7mm/min in order to reduce the calculation time and achieve a reasonable time step that would not give erroneous results in the explicit time integration.

The maximum crosshead displacement corresponding to termination of the simulation in the case of static tests was 25mm for all tests, although the experimental maximum displacement was much greater corresponding to half of the length of the compressed tubes. This selection, even though it was made in order to reduce the computer calculation time, it was justified by the fact that the results obtained by the simulation were very close to the experimental ones (see Figs 1-3). In the case of the impact test, the termination of the numerical simulation corresponded to minimization of the load applied on the crushed tube by the drop weight, just as in the actual experimental conditions where the movement of the drop weight was interrupted when the force on the specimen was not sufficient to continue crushing of the tube.

Despite the obvious symmetric configuration of the square tube compression, modelling of one quarter of the whole structure in order to reduce the calculation time was avoided in all cases except modelling of collapse mode I, considering the findings of the experimental works that indicated non-symmetric propagation of tube wall cracking and unsymmetrical overall crushing of the compressed tubes.

The CFRP tube models comprised only four-node shell type of finite elements with Belytchko-Lin-Tsay formulation [10-11], as the thickness of the tested tubes wall was relatively small. The finite element discretization of the modelled tubes was distinctively different in each particular model, featured by local refinements at the sections of the tubes corresponding to the crush zone of each collapse mode. Especially in the case of the model of collapse mode I, the tube walls were modelled using three layers of rectangular elements instead of the single layer models used for the simulation of the other two collapse modes. This three-layer simplified approach was imposed by the fact that the tube wall laminates of the CFRP tubes that collapsed in progressive end-crushing mode I were splayed in two bundles of plies during axial tube compression with simultaneous formation of a debris wedge of fractured materials between them. The thickness of the shell elements corresponding to the two bundles of plies was slightly less than half of the tube wall thickness, while the thickness of the middle layer was very small. Larger number of layers for modelling the tube walls was avoided –even though this could have resulted in improved accuracy in the modelling of progressive collapse mode I- because this would lead to a tremendous increase of the required calculation time.

Material modelling and composites failure criteria

Material model 55 "mat_enhanced_composite_damage" was selected for the modelling of the CFRP tube walls, as one of the most efficient composite material models in LS-DYNA3D. The particulars of this material model are detailed in the referenced User's and Theoretical Manuals [10-11]. Other material models for composites, such as models 54 and 58 were also tried but were not finally selected, because the computed crushing response of the composite tube in the case of material model 55 was closer to the experimentally observed brittle response of the CFRP tubes. The use of composite material models was combined with appropriate flagging of the shell elements for orthotropic layered composite material model and declaration of material angle for each through thickness integration point. The total number of integration points through thickness was equal to the number of woven fabric layers of each CFRP composite tube detailed in Table 1 .

Simulation of contact between interacting parts

Six in total types of contact interface were used in order to prevent penetration between the geometric boundaries of the parts during their movement and progressive tube deformation.

- The “rigidwall_planar” interface type was used for the contact between the tube and the stationary rigid platen of the press or the drop weight test machine.
- The “rigidwall_geometric_flat_motion” type was used for the contact between the tube and the constantly moving upper head of the press in the case of static tests.
- The “rigidwall_planar_moving _forces” type was used in the case of dynamic tests as the “rigidwall_geometric_flat_motion” contact in the case of static tests.
- The “eroding_single_surface” type was used for the contact between the shell elements of the tube at the various stages of tube crushing.
- The “eroding_surface_to_surface” contact was used only in the case modelling of collapse mode I in the static tests, selected for the contact between the shell elements corresponding to the two continuous fronds that were eroded during axial compression.
- Finally, the “tiebreak_surface_ to_surface” contact was also used only in the case of static tests for the modelling of collapse mode I, to model the bonding between the bundles of plies of the tube wall laminate.

RESULTS AND DISCUSSION

The results obtained by the modelling of the axial tube crushing are separated in two sets, the first one pertaining to the static tests and the other to the impact tests. The first set of results is also sub-divided in three sub-sets, each one corresponding to a mode of collapse of the CFRP tubes in static compression, while such division is not necessary in the case of impact tests where only one collapse mode was recorded in the series of experimental works. Each set consists of a sequence of collapse pictures corresponding to the experimental observations of each particular mode, a comparison diagram that includes the load, *P* - displacement, *s* curves obtained by the experimental works and the finite element simulation, marked with the sequential number of each picture of progressive collapse, and a sequence of collapse pictures created by the post-processor of LS-DYNA3D corresponding to the same displacement as the pictures of the experimental works of each set.

A general comment that must be made with respect to the output of the numerical simulation works, is that the finite element modelling works in LSDYNA presented herein, reproduced successfully the overall crushing response of the composite tubes under axial compressive loading in all three cases of collapse modes, as clearly indicated by the terminal views (a), (b) and (c) of Fig.5 corresponding to collapse modes I, II and III respectively. This was achieved using the same type of composite material model with slight alterations in material parameters even though the crushing behaviour of the CFRP tubes varied from brittle fracture that propagated in an unstable manner to almost ductile deformation that resulted in local tube wall buckling and progressive end-crushing with laminate splaying, despite the extremely brittle nature of the constituent materials of the CFRP tubes, i.e. carbon fibres in the form of woven fabric and thermoset epoxy resin. In the paragraphs that follow the output of the numerical simulation is evaluated and compared to the experimental results for the validation of the finite element models.

Visual comparison of images of progressive collapse

The direct visual comparison of the experimental and numerically generated pictures of the progressive specimen collapse in the series of static tests -parts (a) and (c) of Figs. 1, 2 and 3 respectively - shows that the computed response of the tubes is featured by the macroscopic crushing characteristics that were observed during the compressive testing of the modelled tubes in all three collapse modes.

In the particularly interesting case of collapse mode I, finite element modelling quite satisfactory reproduces the dominant characteristic of this collapse mode – i.e. the formation of two continuous fronds per side of the square tube that spread outwards and inwards under high frictional resistance. However, the elimination of elements corresponding to the middle layer of shell elements in the three-layer model presented here, when the failure conditions of the material model were satisfied, cancelled the possibility to reproduce the formation of a debris wedge between the two fronds. The impact of this mismatch was quite intense in the finite element estimation of the overall crash energy absorption, since the energy dissipation in the friction mechanisms related to the debris wedge were not taken into account.

Comparison of the load- displacement curves

Comparison of the load curves in nearly all modelled static and dynamic tests shows very good agreement between the experimental and numerically computed curves. Almost perfect matching of curves is achieved in the cases of static mid-length collapse mode III and local tube wall-buckling mode II for the entire crosshead displacement. Matching of curves in the other two cases, i.e. progressive crushing with laminate splaying in static axial compression and mid-length collapse in impact testing is very satisfactory in the initial part of the load curve up to a short interval after the tube crushing initiation, but shows slight variations from the experimental results in the middle part, corresponding to intermediate displacement of the cross head. In the particular case of the impact test simulation, despite this variation, force is minimized at almost the same displacement of the drop weight as in the experimental works, and moreover the overall crash energy absorption is approximately equal (96.5%) to the experimental value.

Comparison in terms of the main crushing characteristics

An overall picture of the main crushing characteristics of the modelled static and dynamic compressive tests, i.e. peak load, P_{max}, absorbed crash energy, E_{abs}, is given in Figs 6 and 7 including both experimental and numerically calculated values. Comparison between the results of experimental works and finite element simulation indicates excellent agreement between these two sets regarding the peak compressive load for all modelled static and dynamic tests (the numerically computed values of peak load range between 99.5% to 104.5% of the corresponding experimental values for all modes of collapse).

Regarding crash energy absorption, agreement between numerical and experimental values ranged between 96.5% and 103.5% for all modes of collapse except progressive crushing mode I, where the crash energy absorption is underestimated by 33% approximately. This difference is attributed to the underestimation of the absorbed crash energy dissipated to friction mechanisms between the interacting parts of the crushed tube and the press crosshead. Particularly important with this respect was the failure to reproduce the debris wedge between the two fronds and the simplified approach of the laminate splaying by just three layers of elements only.

Influence of strain rate

As recorded during the experimental works the static peak compressive load was approximately just 70% of the corresponding dynamic one (varying between 51%

and 91%) and the same happened also with the absorbed crash energy for almost all test cases (static E_{abs} ranged between 31% and 69% of the corresponding dynamic one) except the ones corresponding to static collapse mode I. Unfortunately, the formulation of material model 55 in LS-DYNA3D does not allow incorporation of strain rate effects and consequently higher values of strength had to be declared during model preparation in order to accurately predict the higher peak load and absorbed crash energy corresponding to the impact tests.

5. SUMMARY AND CONCLUSIONS

Summarising the main findings and results of the previously described numerical simulation of the static axial compression and impact testing of square CFRP tubes by means of the LS-DYNA3D explicit finite element code, the following conclusions may be drawn:

- Finite element analysis is able to reproduce very satisfactory the various types of collapse modes that were observed in the series of the modelled experimental works despite the extremely brittle nature of the constituent materials of the compressed CFRP tubes. These collapse modes range from mid-length unstable collapse mode –which is the predominant collapse mode, to local tube wall buckling and stable progressive end crushing with tube wall splaying which is the mode of collapse featured by the higher crash energy absorption.
- Reliable modelling of composite tubes crushing response in compression requires the use of effective composite material models –such as the enhanced composite damage material model 55 used in this work- instead of material models more suitable for metals or polymers, in order to adequately model the complex response of a layered fibre reinforced plastic, considering a number of material parameters related to elastic properties and strength.
- Due to inadequate formulation of the existing material models for FRP laminates in LS-DYNA3D, stain rate effects on composite materials that justify the strength increase of the tested CFRP tubes that was recorded in the case of impact tests in the course of experimental works, must be considered in advance when calibrating the material parameters for simulation of dynamic problems.
- Finite element simulation results pertaining to the main crushing characteristics –i.e. peak load and crash energy absorption- are very close to the experimental results, especially in the case of the unstable collapse modes as the mid-length collapse mode that was observed at a frequency of 78% in the total number of static and dynamic tests.

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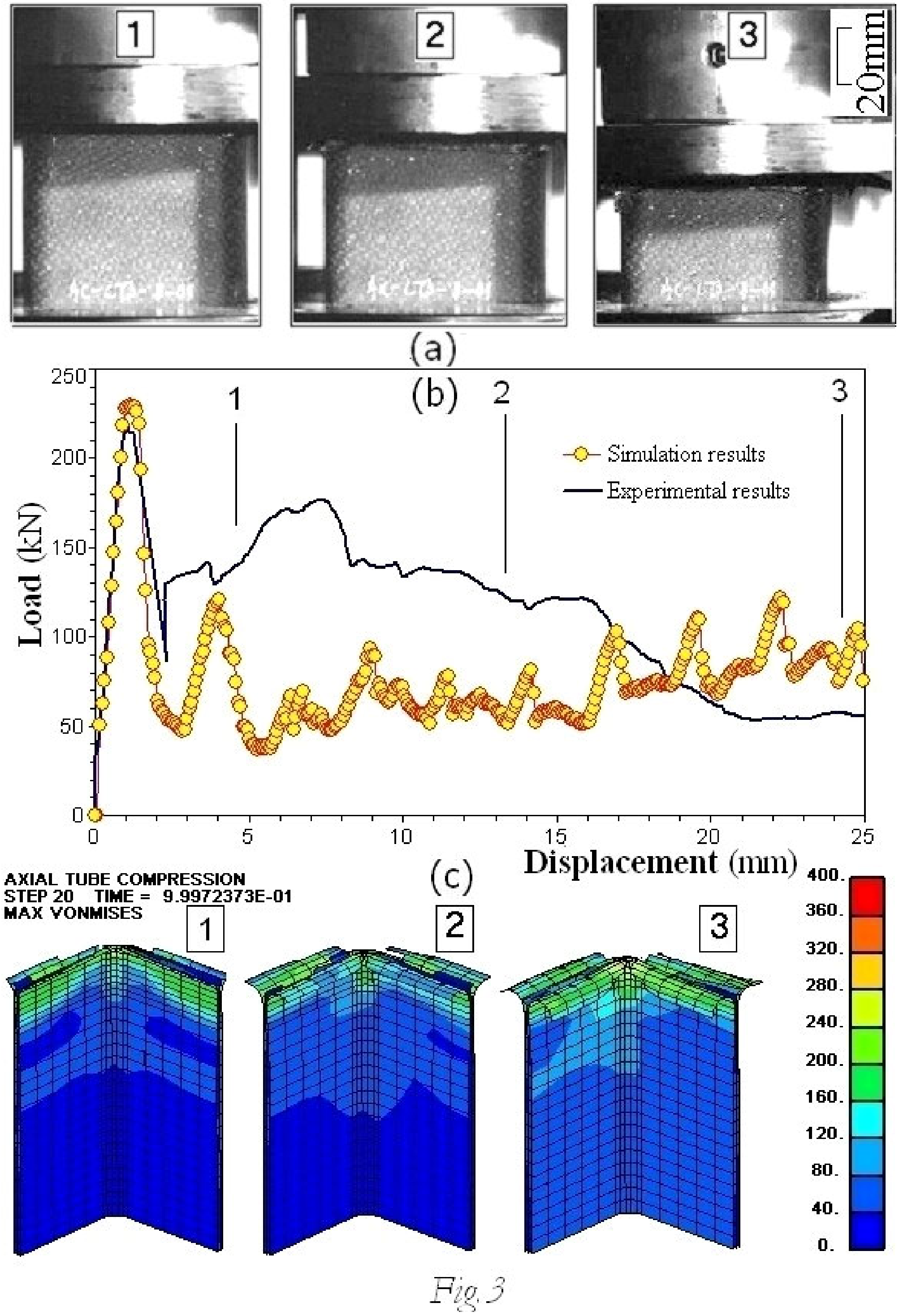


Fig.1 Collapse mode I, progressive end-crushing of specimen AC-CT2-C01 in static compression (a) Pictures of progressive collapse (experimental) (b) experimental and numerical load-displacement curves (c) Pictures of progressive collapse with max von-Mises stress distribution (numerical)

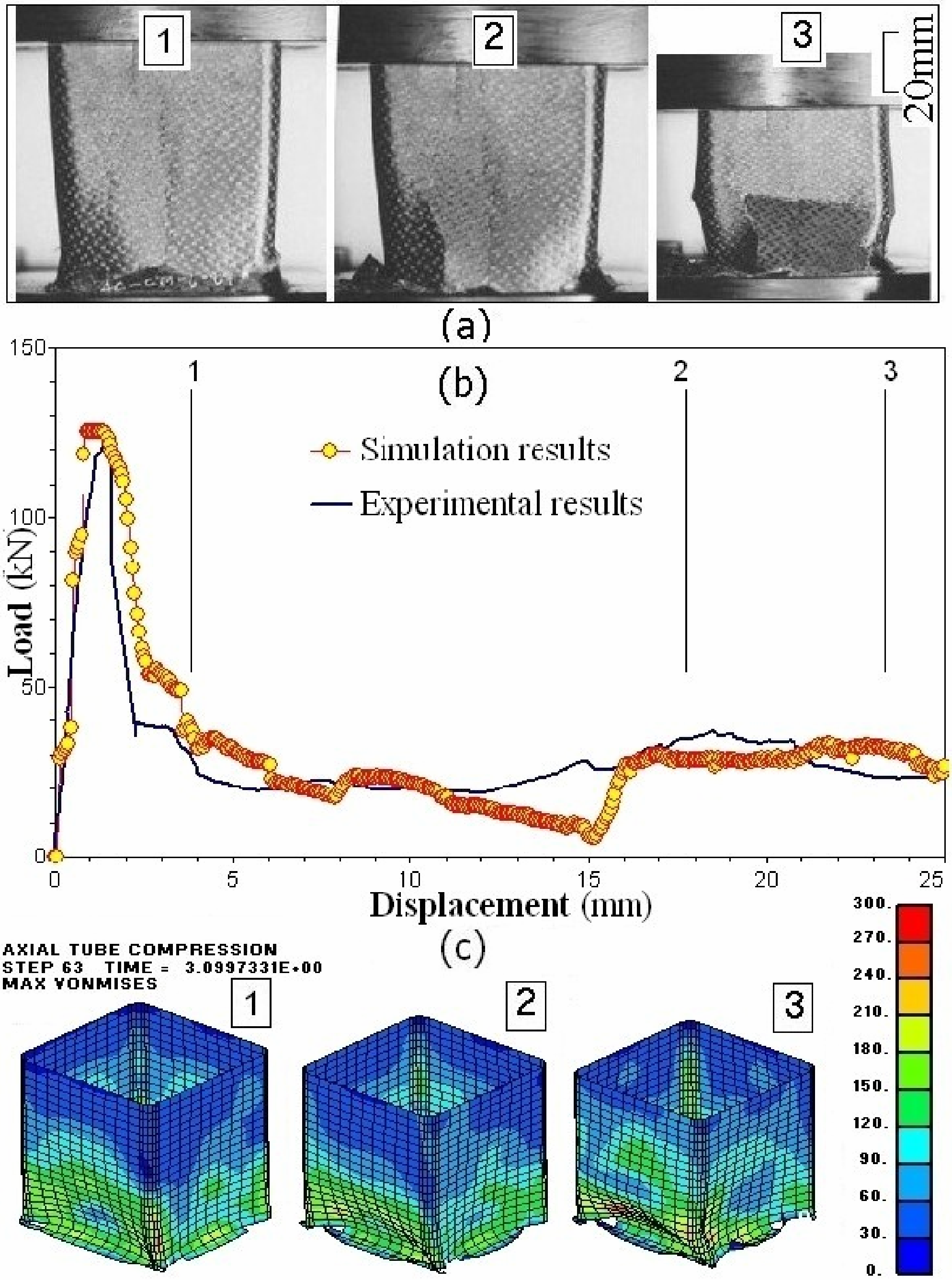


Fig.2 Collapse mode II, local tube-wall buckling of specimen AC-CT1-C01 in static compression (a) Pictures of progressive collapse (experimental) (b) Experimental and numerical load-displacement curves (c) Pictures of progressive collapse with max von-Mises stress distribution (numerical)

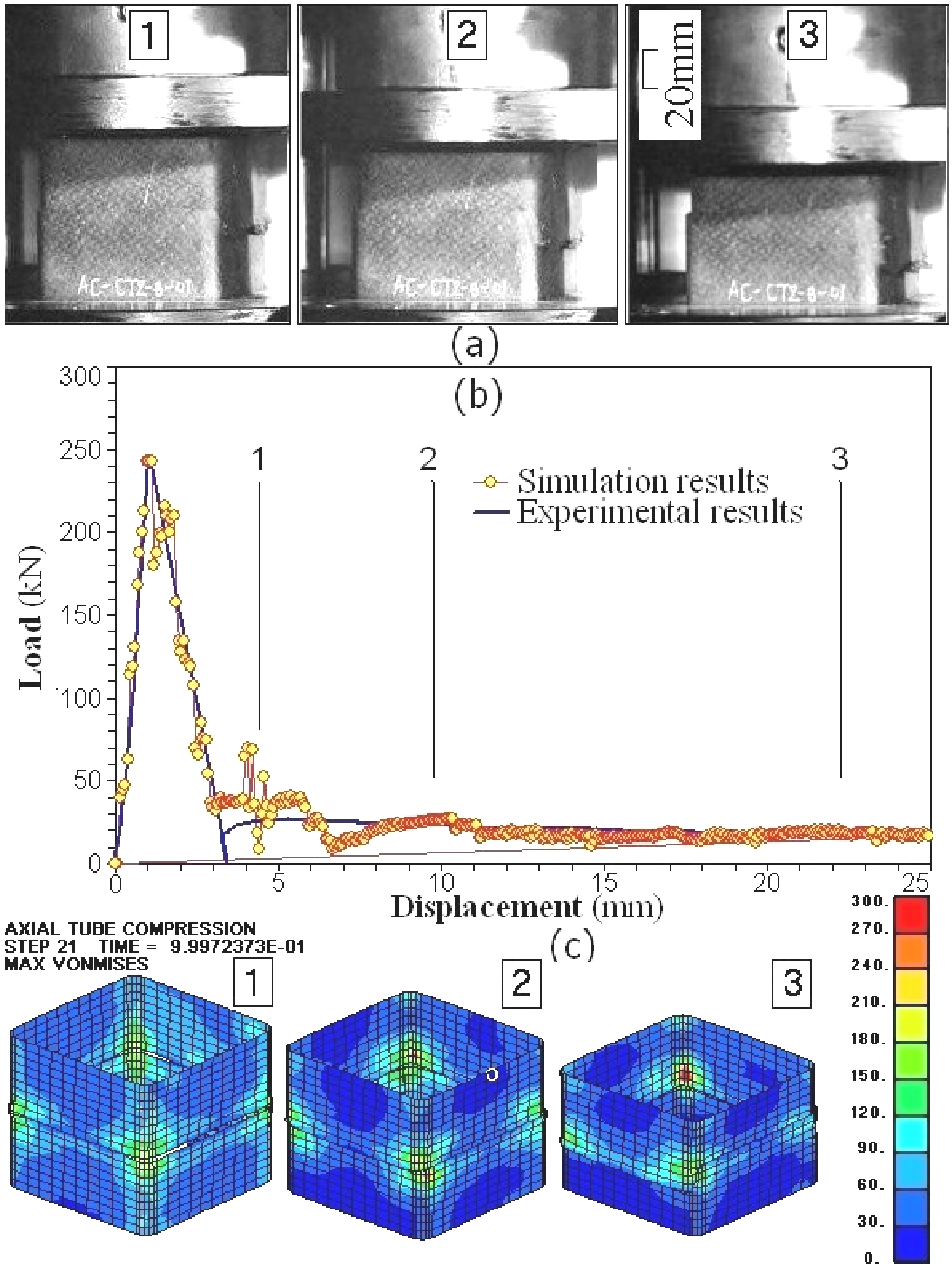


Fig.5

Fig.3 Collapse mode III, mid-length collapse of specimen AC-CT2-B01 in static compression
(a) Pictures of progressive collapse (experimental) (b) Experimental and numerical load-displacement curves (c) Pictures of progressive collapse with max von-Mises stress distribution (numerical)

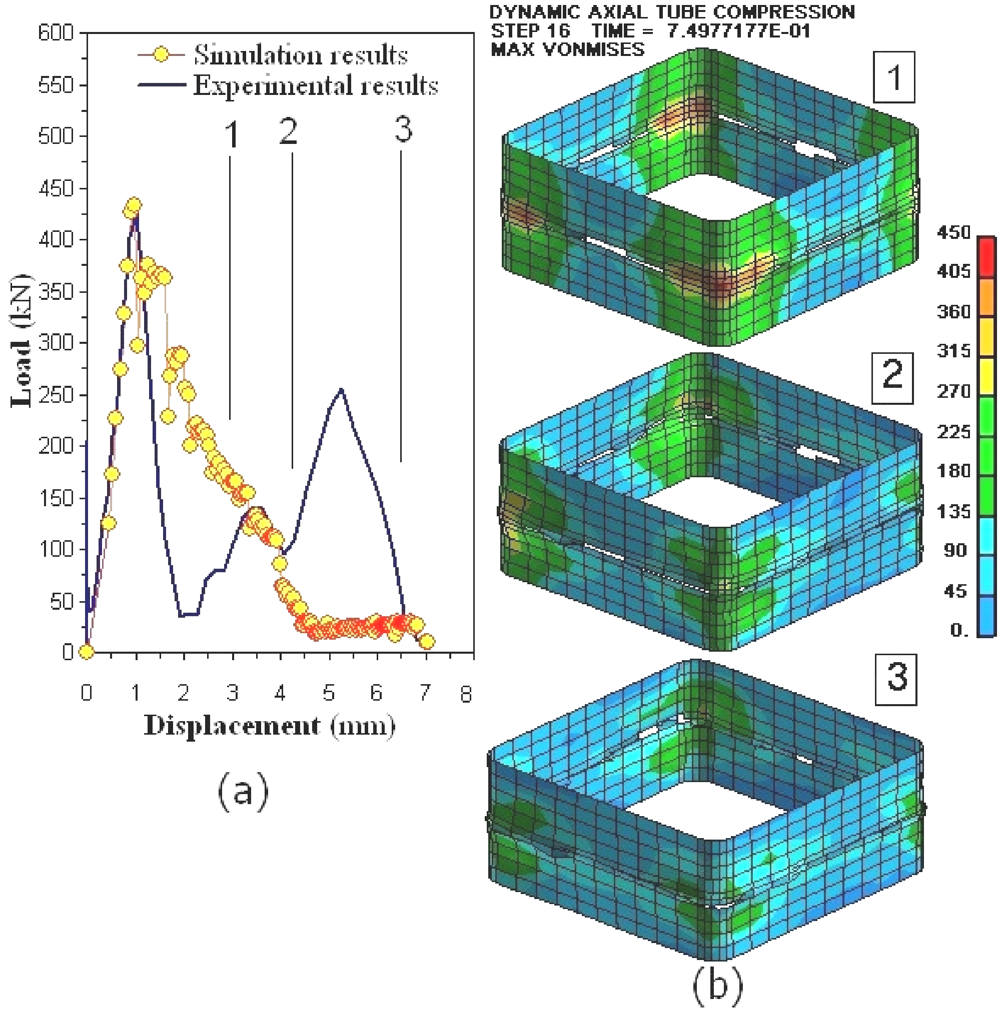


Fig.4 Collapse mode III, mid-length collapse of specimen AC-CT3-A01 in dynamic compression (a) Experimental and numerical load-displacement curves (b) Pictures of progressive collapse with max von-Mises stress distribution (numerical)

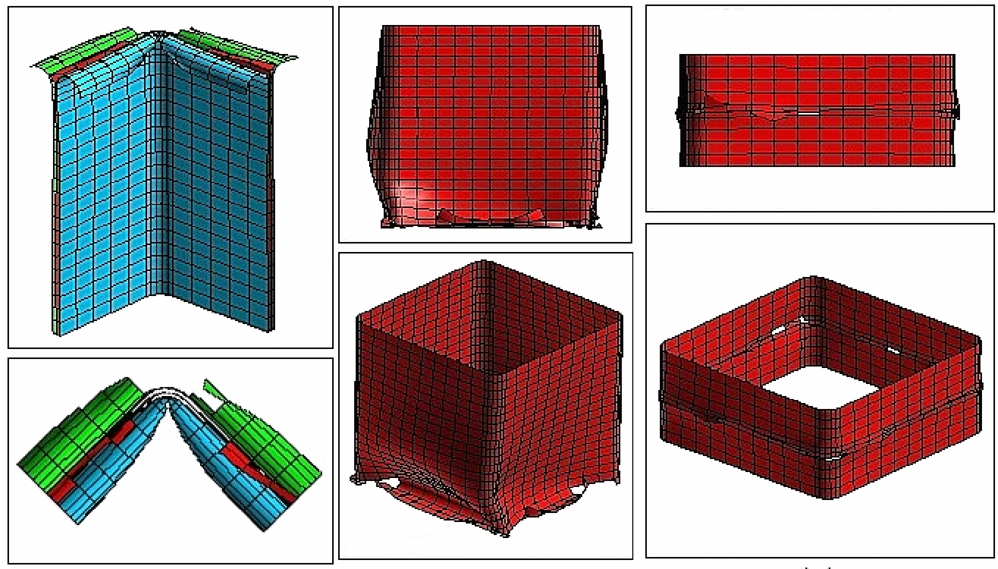
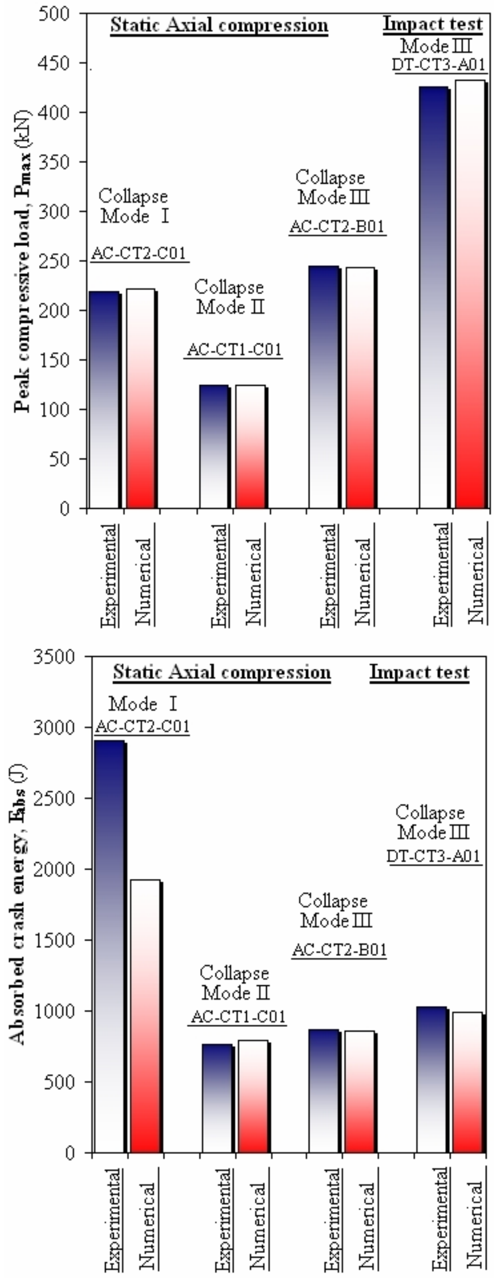


Fig.5 Terminal views of compressed tubes for collapse modes I –III by LS-DYNA3D
(a) Mode I, progressive end-crushing (Static testing of AC-CT2-C01) (b) Mode II, local tube-wall buckling (Static testing of AC-CT1-C01) (c) Mode III, mid-length collapse (Impact loading of DT-CT2-C01).



Figs.6-7 Comparison of experimental and numerical results for the peak load and absorbed crash energy