COLLAPSE BEHAVIOUR OF THIN WALLED SHELLS

By

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Submitted
in fulfillment of the requirements of the Degree of
DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY, DELHI
HAUZ KHAS, NEW DELHI-110016, INDIA
MAY, 2004

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Wear resistance;
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CERTIFICATE

This is to certify that the thesis entitled **'Collapse behaviour of thin walled shells'** being submitted by Mr. Venkatesh to the Indian Institute of Technology, Delhi for the award of the Degree of Doctor of Philosophy is a record of bonafide research work carried out by him. Mr. Venkatesh has worked under our supervision and guidance and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard for the Doctor of Philosophy Degree.

The result contained in this thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

I express my profound sense of gratitude and sincere appreciation to Prof. N.K.Gupta for his untiring motivation, invaluable guidance and constant encouragement throughout this research work. His simplicity, foresightedness, keen interest and immense patience have inspired me towards the completion of this work. The present work is deeply influenced by his technical insight and maturity in identifying new research areas.

I am extremely grateful to Prof. S.K.Gupta for his valuable suggestions, discussions and guidance during this work.

I am grateful to Principal Malnad collage of Engineering, Hassan and Government of Karnataka for providing the deputation under Quality Improvement Programme to carryout this research work. I am thankful to all my colleagues in the department of Civil Engineering, Malnad collage of Engineering, Hassan who shared my workload during the period of this study.

I am thankful to the faculty members of Applied Mechanics Department who helped me at various stages.

I thank Dr. Hussain Abbas, Dr. G.L.Easwara Prasad, Dr. Mohd. Ahmed, Dr. P.K.Gupta and Mr. N.M. Sheriff for their help, guidance and encouragement.

I am thankful to Mr. K.K.Mittal, Mr. B.S.Rana, Mr. Niranjanlal and Mr. Bharat singh and Mr. Narender Kumar for all their advice and help during the experimental work in this thesis.

I also wish to thank to the staff of Computational Laboratory, Departmental Workshop and IDDC for their advice and help.

I sincerely thank all my friends and fellow research scholars, for their encouragement and help.

I express my gratitude to my mother, brothers, sisters, brother-in-laws, sister-in-laws and relatives for their blessings and moral support that made it possible for me to complete this research work.

Lastly but not the least, I express my gratitude to my wife Smt.Yashodha venkatesh, sweet son Chi Jeevan venyas for their inspiration, encouragement, love, affection and forbearance.

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ABSTRACT

Studies on collapse behaviour of aluminium cylindrical, conical and spherical shells were performed under axial compression both in quasi-static and impact loading conditions. Quasi-static testes were conducted on a ZWICK machine and impact tests were conducted on a gravity drop hammer setup. Various problems considered were:

a) Axial compression of cylindrical shells between two flat rigid platens.

b) Axial compression of conical shells between two flat rigid platens.

c) Axial compression of spherical shells between two flat rigid platens.

d) Axial compression of spherical shells under central loading, between a steel flat indenter of 22 mm diameter and a rigid platen.

e) Axial compression of spherical shells under central loading, between a hemi-spherical nosed steel indenter of 22 mm diameter and a rigid platen.

Experiments were performed on cylindrical shells of different diameters and thicknesses, conical shells of different semi-apical angles and slenderness ratios, and spherical shells of different radii and thicknesses. Various failure modes of these shells, their energy absorption capacities, and effect thereon of various parameters were studied. A finite element model for each case has been proposed with the help of finite element code FORGE2, and results obtained have been compared with the results of experiments under both static and impact loading conditions. The material for finite element simulation has been modeled as rigid-viscoplastic. Deformation mechanism of the shells during compression processes in each case of study has been illustrated, analysed and discussed in detail with the help of the contours of different components of stress, strain and strain rate. The experimental and computational results, in the form of deformed

profiles at various stages of compression, and load-compression and energy-compression curves, are presented, compared and found in good agreement.

Analysis was also carried out in some cases by considering hinge formation, and the results obtained have been compared with experiments. A comparative study of the results obtained from the quasi-static and impact tests is also presented. Brief descriptions of the work done on aluminium cylindrical, conical and spherical shells are given below.

Cylindrical shells

Static and impact axial compression tests were performed on aluminium cylindrical shells of D/t values ranging between 11.5 and 31.49. To study the influence of the D/t values of the shell on their modes of collapse and energy absorption capacities, for a group of specimens of same diameter, thickness of the tubes was varied and vice versa. Effects of thickness variation for same diameter tubes and effect of diameter variation for the tubes of same thickness, were investigated. Most of the aluminium cylindrical shells tested in the present study under both quasi-static and impact loading were found to collapse in axisymmetric concertina mode.

A finite element model for each case of study has been proposed and verified for both static and impact loading conditions with the help of finite element code FORGE2. The predicted load-compression and energy-compression curves are found to match well with those obtained from experiments. The variation of the initial peak load, mean crushing load, energy values, inner and outer radii, folding parameter (m- ratio of the inside to the total fold length) and size of fold has also been found to match well with the experiments.

Modes of collapse of aluminium cylindrical shells tested under the impact of a drop hammer are found to be almost same as those observed in quasi-static tests. But the energy absorbing capacity in impact test is increased by about 1.56% to 12.3% in comparison with the static test values. The initial peak load values in impact experiments were found to be higher by about 14.33 % to 40.25% than their corresponding static values. The impact mean collapse load and folding parameter values are also found to be higher than the corresponding static values. A comparison of computed results show that the values of hydrostatic pressure, nodal velocities, equivalent strain rate, equivalent strain, equivalent stress and maximum principal stress values in impact are higher than the corresponding static values.

Based on the mechanisms of collapse observed in the quasi-static tests, an improved version of partially outside and partial inside straight fold mathematical model has been developed. All the variables involved in the analysis such as, the size of fold, folding parameter, the mean crushing load and the load-compression curve have been computed. The results obtained compare well with the experiments.

Conical shells

Static and impact axial compression tests were performed on aluminimum conical shells of semi-apical angles varying over a wide range from 6.84° to 65.35° and the mean diameter to thickness (D/t) ratio varying from 22.32 to 79.29. The specimens employed were of different semi-apical angles and same thickness, different thickness and same semi-apical angles; same semi-apical angles, different depths and same bottom diameter; and same semi-apical angles, different depths and same top diameter. Modes of collapse and energy absorbing capacity of the shells and influence thereon of semi-apical angles, thickness, depth, and top and bottom diameters of the shells were investigated. The modes of collapse and the load-compression curves were seen to be highly influenced by the semi- apical angle of the conical shell. The frusta with lower semi-apical angles (less than 30.66°) were found to collapse by the formation of an axi-symmetric ring, followed by diamond fold mechanism. The shells of higher semi-apical angles (greater than 30.66°) were found to collapse with the formation of an axi-symmetric rolling plastic hinge. In relatively thinner shells (thickness less than or equal to 2 mm), some integral number of non-axisymmetric stationary plastic hinges are formed in the later stages of compression. The shells with semi-apical angle 65.35°, showed reverse bending at their larger end in addition to the rolling plastic hinge formed at the smaller end. The conical shells of semi-apical angle 30.66°, behaved like cylindrical shells until certain initial depth of compression in an axi-symmetric ring mode. Thereafter the progressive collapse of the shell was accompanied by the formation of axi-symmetric inward dimple and non-axi-symmetric integral number of lobes.

A finite element model for each case of axi-symmetrical deformation has been proposed and verified for both static and impact loading conditions with the help of finite element code FORGE2. The predicted load-compression and energy-compression curves are found to match well with those obtained from experiments. The variation of the mean crushing load, energy values, characteristic dimension and radius of rolling plastic hinge has also been found to match well with the experimental values.

Modes of collapse of aluminium conical shells tested in impact are generally found to be same as those observed in their quasi-static tests. But the energy absorbing capacity in impact test is increased by about 8.93% to 49.6 % in comparison with the static test values. The impact mean collapse load and the radius of rolling plastic hinge values are found to be higher than the corresponding static values. The computed values of hydrostatic pressure, nodal velocities, equivalent strain rate, equivalent strain, equivalent stress and maximum principal stress under impact loading are also found to be higher than their corresponding static values.

Based on the mechanisms of collapse observed in the quasi-static tests, an analytical model is presented for prediction of load-compression and energy-compression curves, as well as mean collapse loads for frusta which collapsed due to rolling and stationary plastic hinges. The results obtained from the analytical model matched well with those from the experiments.

Spherical shells

Static and impact axial compression experiments were conducted on aluminium spherical shells of radius to thickness (*R*/*t*) ratios varying from 16.46 to 53.13. Specimens were placed on flat rigid platen and compressed by a flat platen in one set of experiments and by a 22 mm diameter cylindrical indenter with flat or hemispherical nose in the second set. The specimens employed were of different thickness and same radius; different radii and same thickness; and different depths and same base radius and thickness. The modes of collapse and energy absorbing capacity of the shells were studied and influence thereon of various parameters is discussed. In quasi-static tests, aluminimum spherical shells were found to collapse due to the formation of axi-symmetric inward dimpling associated with a rolling plastic hinge. The shells of high R/T values, in the later stages of compression have shown buckling with non-axisymmetric shape, consisting of integral number of lobes and stationary plastic hinges formed between consecutive lobes. The variation of the radius of the rolling plastic hinge with compression has been studied from the experiments, and typical variation is presented.

A finite element model for each case of study has been proposed and verified for both static and impact loading conditions with the help of finite element code FORGE2. The predicted load-compression and energy-compression curves are found to match well with those obtained from experiments. The values of the mean crushing load, energy values, characteristic dimensions and radius of rolling plastic hinge have also been found to match well with the experimental values.

Modes of collapse of aluminium spherical shells tested in impact tests are found to be same as those observed in their quasi-static tests. But the energy absorbing capacity in impact test is increased by about 5.4 % to 27.82 % in comparison with the static test values. The impact mean collapse load and the radius of rolling plastic hinge values are found to be higher than their corresponding static values. The computed values of hydrostatic pressure, nodal velocities, equivalent strain rate, equivalent strain, equivalent stress and maximum principal stress are found to be higher than the corresponding static values.

Based on the mechanisms of collapse observed in the quasi-static tests, an analytical model has been developed for the prediction of load-compression and energy-compression curves. The results obtained from the analytical model compared well with the experiments.

Spherical shells were also subjected to quasi-static and impact tests, where in these were compressed between a 22 mm diameters flat or hemi-spherical nosed indenter and a flat platen. The modes of collapse thus obtained are presented and compared with those obtained in the case of compression between two flat platens. Finite element code FORGE2 is employed to analyse the deformations and results obtained for the load-compression curve, shapes of deformed specimens, radius of rolling plastic hinge, and mean collapse load and energy absorbed values, have been compared with experiments.

Thus the thesis presents an extensive experimental study of the collapse behavior of thin walled shells viz., aluminium cylindrical, conical and spherical shells. A finite element model for each case of study has been proposed and verified with the help of finite element code FORGE2. Simple analytical models are also presented for the prediction of load-compression and energy-compression curves, and mean collapse loads.

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