CHAPTER 7

CONCLUSIONS AND FURTHER RESEARCH

7.1 CONCLUSIONS

The conclusions derived in this section are based on the numerical and experimental studies conducted in the present work using the test cylindrical shells taken for study.

(i) From the study about the effect of size variation and angles of inclination of dent (for assumed dent geometry) on buckling strength of a short thin cylindrical shell discussed in Chapter 4, the following conclusions are derived. Two material models are considered for analysis and some of the common conclusions derived are as follows

1. Either a longer or a shorter dent on thin perfect cylindrical shell reduces the buckling strength of cylindrical shell drastically because dents tend to store the load as bending energy which is several orders lower than membrane strain energy.

2. When the axial load is applied on a cylindrical shell with a dent of any size and any angle of inclination, local deformations consisting of two ridges, four trough surfaces and two bridge surfaces are formed around the dent.

3. When the axial compressive load is applied on the thin cylindrical shell the formation of local elastic deformation (ridge and trough surfaces formation) increases the stiffness of the cylindrical shell in the dent effective region (if this formation is not there, the strength in that region will be very much lower because load applied is stored as bending energy and hence result in much earlier collapse).
4. Through the trough surfaces only the load is applied on dent tips and since the dent tips exhibit resistance for deformation, stresses are concentrated around the dent tips.

5. The stress values in the bridge surfaces are always less than other regions because the trough surfaces act as stiffeners and do allow only less load through bridge surfaces.

6. The load applied on the cylindrical shell is shared by the dent effective region and the perfect cylindrical shell portion other than dent effective region but, the limit load of the thin cylindrical shells with a dent mainly depends on the load carrying capacity of the perfect cylindrical shell portion other than dent effect region and also the stiffness of the dent due to its orientation. As the angle of inclination of dent increases, circumferential width of dent effective region decreases resulting in increased area of the perfect cylindrical shell portion to support the load and also the stiffness of dent increases and there by increases the limit load.

7. For any dimensions of dent, circumferential dents (i.e., zero inclination of dents) have more dominant effect in reducing the buckling strength compared with other angles of inclination of dent.

8. Thin cylindrical shells with longitudinal dents have higher buckling strengths by approximately 5 to 6% than cylindrical shells with circumferential dents because the net effect of reduction of load carrying capacity due to the dent effective region and increase in load carrying capacity due to dent stiffness cause the cylindrical shell, with a longitudinal dent to have buckling strength closer to buckling strength of cylindrical shell without dent and at the same time higher buckling strength than cylindrical shells with a circumferential dent.

9. From $0^\circ$ to $30^\circ$ angles of inclination of dent the effect of both the angle of inclination and width variation on buckling strength seems to be negligible. This is because both angles of inclination and width
variation do not affect the circumferential width of dent effective region and therefore there is no change in the perfect thin cylindrical portion resulting in almost same buckling strength.

10. The circumferential dents are sensitive for length and depth variation but insensitive for width variation. The longitudinal dents are sensitive for width variation only but insensitive for dent length variation and have meager effect for dent depth variation. Similarly, dents with all other angles of inclination are sensitive to length, width and depth variations of dent.

11. Shorter dents (length <40t) do not have much effect for angles of inclination and depth variation up to 3t in reducing the buckling strength of cylindrical shells, because the size of the dent is small.

(a) Stainless Steel Cylindrical Shell

12. Both the longer and shorter dents reduce the buckling strength of stainless steel cylindrical shell drastically with maximum reduction of nearly 64.5 % of buckling strength of perfect cylindrical shell

13. The stiffness of the cylindrical shell decreases gradually as the load applied increases and at the limit load condition the stiffness becomes zero.

14. The stress values in the bridge surfaces are always less than other regions because the trough surfaces act as stiffeners and do allow only less load via bridge surfaces and also the longitudinal edges of dent provides less resistance to support the load thereby allowing local deformation.

15. Up to 60° angle of inclination of dent, the complete dent geometry reaches the plastic condition and just before limit load condition, two partial rings of plastic zones excluding dent effective region one nearer to the loading edge and other nearer to support edge are
formed. In case of $75^\circ$ and $90^\circ$ angles of inclination only some parts of dent geometry reaches the plastic condition, when the width of the dent is considerably higher and in case of longitudinal dents no plastic condition is seen inside the dent geometry. Here also just before limit load condition, two rings of plastic zones excluding dent effective region are formed at the edges of the cylindrical shell. Hence it can be concluded that the plastic stress condition inside the dent geometry mainly depends on the amount of load supported by the dent effective region and dent stiffness due to the angle of inclination of dent.

(b) Carbon Steel Cylindrical Shell

16. Both the long and short dents reduce the buckling strength of cylindrical shells drastically with maximum reduction of nearly 52.5% of buckling strength of perfect cylindrical shell.

17. In general, for the same size of thin cylindrical shell with a dent, stainless steel thin cylindrical shells have lower buckling strength than carbon steel thin cylindrical shells as discussed in Ref. (Hautala).

18. In all the cases, only some spots on the dent geometry and trough surfaces reach the plastic condition, but just before reaching limit load condition by forming two rings of plastic zones excluding dent effective region one nearer to the loading edge and other nearer to support edge, the cylindrical shells collapse.

19. The stiffness of the cylindrical shell remains constant just up to the limit load condition and as soon as the rings of plastic zones are formed excluding dent effective region at both the edges of the cylindrical shell, it collapses suddenly.
From the study about the neighborhoodness effect of circumferential short dents (for assumed dent geometry) on buckling strength of short thin cylindrical shells discussed in Chapter 4, the following conclusions are derived. Two material models are considered for analysis and some of the common conclusions are as follows

1. The maximum reduction in buckling strength of a stainless steel cylindrical shell with a dent of size \( L=40t \), \( W=20t \) and \( D=3t \) is 63.12% but with two circumferential short dents maximum reduction in buckling strength is only 63.7%. Whereas in case of carbon steel cylindrical shell the maximum reduction in buckling strength of a cylindrical shell with a dent of size \( L=40t \), \( W=20t \) and \( D=3t \) is 53.41% but with two circumferential short dents maximum reduction in buckling strength is only 54.55%. From this it can be understood that the effect of two short dents and its nearness effect seem to be negligible compared with effect of single dent in reducing the buckling strength of the cylindrical shell. Similar conclusions were also derived in Wullschleger (2006). And also here once again it is proved that the buckling strength of stainless steel cylindrical shells are less than that of carbon steel cylindrical shells as discussed in Ref. (Hautala).

2. In case of a cylindrical shell with a single circumferential dent, ridge-trough surface formation consists of two ridges, four trough surfaces and two bridge surfaces can be seen in the dent effective region. And in case of a cylindrical shell with two circumferential dents when the gap is more than half bending wavelength, there is a middle ridge-trough surface formation in addition to the above in its dent effective region is seen. Because of this additional middle ridge-trough surface formation the strength of the dent effective region is slightly more than the strength of the dent effective region of single dent.
3. In both the cases of stainless steel and carbon steel cylindrical shells, when the gap between two circumferential dents are less than half bending wavelength (i.e., when the center distance between dents is 60mm and 80mm) the two dents merge together and formed into single long dent and fails at limit load condition when the slope of the stiffness curve becomes zero. Before reaching this limit load condition, rings of plastic zones excluding dent effective region are formed at the edges of the cylindrical shell.

4. In case of two circumferential short dents with a gap greater than half bending wave length (i.e., when the center distance between dents is more than 100mm), because of additional middle trough surface formation in the dent effective region, its strength increases slightly and thereby load shared by it also increases slightly. Because of this reason, in case of stainless steel cylindrical shells (forming plastic zone only in the dent geometry), the cylindrical shells fail at limit load condition of zero stiffness before the formation of rings of plastic zones at the edges of the cylindrical shell. Whereas the carbon steel cylindrical shells fails by forming rings of plastic zone at the loading and supporting edges before reaching the limit load condition.

5. Here also it can be concluded that buckling strength of cylindrical shell with dents mainly depends on the load carrying capacity of the perfect cylindrical shell portion other than the dent effective region since both the dents are circumferential dents.

(iii) From the study about the mirror image random geometrical imperfect stainless steel short cylindrical shell models in Chapter 5, the following conclusions are derived

(a) Mirror Image Random Imperfection Models

1. In all the cases of random imperfect cylindrical shell models (with RMS values 0.45mm and 0.93mm and with maximum amplitude of imperfections 1.32mm and 3.7mm), the maximum buckling strength
variation between a pair of mirror image models is approximately between 5 to 6%.

2. In all the cases, multiple plastic zones are seen on the cylindrical shell before reaching the limit load condition mostly between the supporting edge and just above half the height of the cylindrical shell and no plastic zones are seen near the loading edge.

3. Before reaching the limit load condition, the stiffness of the cylindrical shell becomes zero.

4. The variation of buckling strength between a pair of mirror image imperfection models is mainly due to the curvature present in the cylindrical shell and not primarily due to circumferential interactions between the initial imperfections because of the closed structural form of the cylindrical shell. This is proved by conducting numerical studies of random imperfect cylindrical panel and thin flat plate models. In case of cylindrical panels, buckling strength variations between a pair of mirror image random imperfection models exist, whereas in case of thin flat plate models, buckling strength variation between a pair of mirror image random imperfection models vanishes.

(b) Mirror Image Axisymmetric Imperfection Patterns

When even numbers of longitudinal half lobes are present in the cylindrical shells, both the models and its mirror image models give out same buckling strength. And when odd numbers of longitudinal half lobes are present in the cylindrical shells, both the models and its mirror image models give out different buckling strengths. Further when the central half lobe is of inward half lobe, the reduction in buckling strength is more than that of outward central half lobe.
(c) **Mirror Image Asymmetric Imperfection Patterns**

The cylindrical shells with mirror image asymmetric imperfection patterns will have same buckling strength because the mirroring of asymmetric imperfection pattern is nothing but rotating the model with imperfections by an angle of \((90/n)\), where \(n\) = number of circumferential half lobes.

(d) **Reliability Calculations**

1. The reliability predictions using the simple reliability method presented in this thesis for the case of maximum amplitude of imperfections ±1.32mm is such that when the applied load is 18.7% of the buckling strength of the perfect cylindrical shell, 100% reliability is expected and for 20.8% of the buckling strength of the perfect cylindrical shell, 0% reliability is expected.

2. The strength distribution of random imperfect cylindrical shell models with maximum amplitude of imperfections ±1.32mm matches better with the left side of the normal distribution curve. Whereas in the case of strength distribution of random imperfect cylindrical shell models with maximum amplitude of imperfections ±3.7mm, the left side of the distribution fairly matches with normal distribution curve. And in the other two cases of strength distribution with RMS value of 0.45mm and 0.95mm, the strength distribution badly matches the normal distribution curve. From the above, it can be concluded that for better reliability predictions, more number of random models using more number of eigen affine mode shapes are needed.
From Chapter 6, the experimental work carried out on aluminum thin cylindrical shells having both distributed geometrical imperfections and dent formed on it, the following conclusions are derived.

1. Since the thin cylindrical shells taken for study is relatively thick \( r/t = 47.3 \), the effect of distributed geometrical imperfection patterns and slight variation maximum amplitude of imperfections on buckling strength were found to be negligible.

2. Buckling strength of cylindrical shells with a longitudinal dent are higher than buckling strength of cylindrical shells with a circumferential dent. The maximum and minimum buckling strength variation between the cylindrical shells with circumferential and longitudinal dents are approximately in the range of 3.4% to 6.9%.

3. The buckling strength of cylindrical shells with a longitudinal dent are closer (approximate in the range of 0 to 1.7%) to buckling strength of cylindrical shells without dent but containing only distributed geometrical imperfections.

4. In case of test cylindrical shells without dent, the plastic bulge patterns were noticed at top and bottom edges of the cylindrical shells when the load on the cylindrical shells reach the limit load condition.

5. In case of cylindrical shells with a circumferential dent at limit load condition plastic deformations were noticed on the dent geometry and on further loading beyond limit load condition, a partial ring of plastic zone was formed at the top edge of the cylindrical shells (excluding the dent effective region) and on further loading, dent geometry also extended along the longitudinal axis of the dent.

6. In case of test cylindrical shells with a longitudinal dent, on limit load condition partial ring of plastic bulge was noticed at the top edge of the cylindrical shells away from the dent effective region. And on further loading beyond limit load condition the longitudinal dent also
plastically deformed forming circumferential lobes at half the height of the cylindrical shells i.e. along the transverse axis of the dent and fails like circumferential dent.

7.1.1 General conclusions

With the FE model simulation evolved/formed in this research work, designers can estimate the safe buckling loads for the finished products (thin shells) with the associated manufacturing and material handling defects like random geometrical imperfections, dent marks etc., with greater confidence and hence alter the load values, if necessary, which the shells are designed to carry originally.

Since no closed form analytical solution for such situations are listed in design books to reckon the inaccuracies of manufacturing and material handling in the design stage itself, the outcome of this research work will definitely fill such a vacuum in design analysis of thin shells and will sure be a handy tool for shell designers.

The foremost and significant contribution of this piece of research work to the world of designers is enhancement of safety, with relatively less complexity of structures of strategic importance, thereby making design a joyful experience rather than a painful one (a general grumble about design).

7.2 FURTHER RESEARCH

- In the present work, effect of dent size and angles of inclination on buckling strength of cylindrical shells are studied in detail by modeling the dent geometry on the perfect cylindrical shell geometry. Similar numerical simulations of combined effect of both distributed geometrical imperfections and dent(s) can be carried out as one of the future works assuming the distributed geometrical imperfections as
first eigen mode shape or of some other known form of worst imperfection shape.

- In the work of Athiannan and Palaninathan (2004), it was concluded that the extent of imperfections (imperfections present over an area) rather than the magnitude of imperfection (the highest value in a model) is important in assessing the buckling load. Numerical studies can be performed to verify this conclusion using random geometrical imperfection models generated in the present study.

- In the future research work, some guidelines can be established for determining the number of eigen affine mode shapes used in the in the modeling of random geometrical imperfections to generate enough number of BSR values for accurate prediction of reliability of the structural member.

- In most of the research works, the measured geometrical imperfections are represented by double Fourier series. But in the case of combined distributed geometrical imperfections and dent consisting of both shallow radial amplitudes of imperfections and deep radial amplitudes of imperfections in a model requires better mathematical representations over the conventional Fourier series representation. Hence, it is essential to study about the better mathematical representations of geometrical imperfections consisting of both shallow radial amplitudes of imperfections and deep radial amplitudes of imperfections in a model.

- Knowing mathematical representations of imperfections consisting of both shallow radial amplitudes of imperfections and deep radial amplitudes of imperfections in a model, numerical simulations to predict the buckling strength of the test cylindrical shells can be carried out and validated with experimentally predicted buckling strengths of test cylindrical shells.