

Finite Element Analysis Up To Failure Of Composite Concrete – Corrugated Steel Cylindrical Shells

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Abstract

This study presents three-dimensional finite element analysis to the behavior of composite concrete-corrugated steel cylindrical shell. This type of construction utilizes the advantages of both of ordinary reinforced concrete and the composite action of cylindrical shell with corrugated steel plates. The 8-node brick elements in (ANSYS v.9.0) have been used to represent the concrete, while the steel bars are modeled as discrete axial members connected with concrete elements at shared nodes with the assumption of perfect bond between the concrete and the steel bars. The corrugated steel plate is modeled by four-node shell elements. The interface elements are modeled by using three-dimensional surface to surface contact elements connected with the nodes of concrete and steel channel elements. Comparison is made between the results obtained from the finite element analysis and the available experimental results of previous studies.

Keywords: composite, concrete-corrugated steel, cylindrical shell, finite element, failure load, ANSYS.

التحليل بالعناصر المحددة لحد الفشل للصفائح القشرية الاسطوانية المركبة من الخرسانة المسلحة والصفائح الفولاذية المتموجة

الخلاصة

تقدم هذه الدراسة بحثاً نظرياً لسلوك الصفائح القشرية الاسطوانية المركبة من الخرسانة المسلحة والصفائح الفولاذية المتموجة. إن هذا النموذج من البناء يجمع الفوائد الموجود في الصفائح القشرية الاسطوانية من الخرسانة المسلحة والصفائح الفولاذية المتموجة المثبتة في السطح الأسفل من القشرة. تم استخدام عناصر طابوقية ذات الثمانية عقد في برنامج (ANSYS). ولتمثيل قضبان حديد التسليح استخدمت عناصر محورية منفصلة مرتبطة مع العقد للعناصر الطابوقية مع افتراض وجود ترابط تام بين الخرسانة وحديد التسليح، وتم استخدام العناصر القشرية ذات العقد الأربعة لتمثيل الصفائح الفولاذية المتموجة. أما المنطقة البيئية فقد تم تمثيلها باستخدام عناصر وسيطية ثلاثية الأبعاد متوافقة مع العناصر الفولاذية والخرسانية ومرتبطة معها عند العقد المشتركة. تمت مقارنة النتائج التي تم الحصول عليها من التحليل بواسطة العناصر المحددة مع نتائج عملية متوفرة وبصورة عامة أظهرت نتائج المقارنة حصول توافق جيد.

Introduction arched composite system:

Many thin concrete shells have been built around the world as large span roofs, but their use has gradually declined over the past few decades. This decline has been due mainly to the high cost of construction and removal of temporary formwork and associated falsework for concrete casting in the construction of a thin concrete shell⁽¹⁻⁴⁾. This rather labour intensive and costly process of construction, but coupled with the increasing ease in analyzing complex skeletal spatial structures offered by advances in computer technology, has made concrete shells much competitive than they were several decades ago⁽¹⁻⁴⁾. This is the present study concern subject; which was invented by **Zeman & Co Gesellschaft, 2004**⁽⁵⁾. The arch deck system is a composite flooring system for building and industrial construction. This type of composite shell deck contains three basic materials: arched corrugated plates, I-section tie bars, dowelling studs for steel section and concrete which are connected between each other as shown on next feature terms with details. The system links the concept of slim - floor ceiling (i.e. composite floor with an integrated (encased) steel girder paired with lower overall floor thickness and integrated fire protection) to the concept of the self - supporting trapezoidal arched sheet, Figure (1).

Unit action of system components:

Component of studied system as prepared in figure (2) work according to the nature of following elements⁽⁵⁾:

§ **Steel girder:** In addition to supporting the edge of arched plate and preventing the slip

between concrete and steel at their connection, the web compensates the compressive forces of the concrete by direct attachment.

§ **The bolts:** The required bolts for securing the necessary compound effect are located on web of steel girders.

§ **Bearing angle:** This is used for supporting the arch plate and redistributes the applied stress on web of steel girder.

§ **Tie- rods:** These are used to resist the horizontal forces acting on the support. Their use is at spaces (2-3) m and this distance depends on the horizontal force. Also the tie-rods lead to increase the surcharge.

In addition to these components, arched corrugate steel plate is used which work as a support to the reinforce concrete mass

Advantages of the system:

In addition to the main benefit, it is found that in any composite structure there are several points obtained from using this system

- Larger spacing of girders allows construction without beams. Thus less number of single components are required and speedy assembly is facilitated.
- Due to the omission of usually required temporary support, saving in scaffolding and working hours are achieved.
- Shorter overall construction periods, as below floor areas, are immediately accessible for further construction work.

- Placing concrete for the composite girder and ceiling in one working process.
- No retouching necessary, i.e. at closing assembly recesses at connections of girders and columns etc.
- Integrated fire protection for steel girder.
- Finished soffit ,also available in color
- The tie-backs required in the stage of construction may stay in the final stage and be utilized as suspension for fixture or lighting.

General behavior of material properties:

A composite structure consists of two or more basic members of different materials according to their behavior under their loading system. The combination changes the physical properties of the composite structure and leads to distribute the stresses in the composite mass. So the design of composite structures for buildings and bridges is mainly concerned with the provision and support of the load – bearing horizontal surface. In Figure (3), concrete reaches its maximum compressive stress at strain ranges between 0.002 and 0.003, and at higher strains it crushes, losing almost all its compressive strength. Concrete is very brittle in tension having strain capacity of about 0.0001 (i.e. 0.1 mm per meter) before it cracks. Also the figure shows that the maximum stress reached by concrete in beam or column...etc, is little more than 80% of its cube strength. Steel yields at strain almost similar to that given for peak stress of concrete, but on further straining the stress in steel continues to increase slowly, until total strain is at least 40 times the yield strain. From above the composite concrete - steel

structure has brittle concrete usually in compression zones and ductile steel in tension zone⁽⁶⁻⁸⁾.

Numerical expression of brittle concrete material:

This New Expression was invented to describe uniaxial stress – strain relationships for concrete in compression. Several equations were adopted by researchers, **Kachlakev and Miller, 2001**⁽⁹⁾ (Equations 1 and 2) with the sequence of periodical operation until reaching the maximum compressive stress at the ultimate strain stress :

$$f = \frac{E_c e}{1 + \left[\frac{e}{e_o} \right]^2} \quad ..(1)$$

$$e_o = \frac{2 f_c}{E_c} \quad ..(2)$$

where:

f = stress at any strain.

ε = strain at stress f .

ε_o = strain at the ultimate compressive strength f_c '.

Table (1) shows the simplified compressive uniaxial stress-strain relationship that was used in this study.

Steel reinforcement:

Steel reinforcement is used to reinforce against concrete tensile stresses or to share concrete in compression. For this study, the steel in the finite element models is assumed to be an elastic - perfectly plastic material with identical behavior in tension and in compression Poisson's ratio of 0.3 is used for the physical properties of steel as substantiated by experimental investigation **Kachlakev and Miller, 2001**⁽⁹⁾. The stress – strain relationship of steel as used in this study is shown in table (3).

Corrugated steel plate:

As given in table (2), the corrugated steel plate is assumed to be a steel reinforcement and as a linear elastic material with the physical properties as discussed in steel reinforcement above. In this study, I - section, tie bars and bolts used for fixity of the composite shell of concrete - corrugated steel plate are neglected in the analysis as they undergo no motion in their locations.

Finite element modeling:

The finite element method is a numerical procedure that can be used to obtain solution to a variety of problems of engineering. So it is a suitable method and it is adopted in this work to analyze the composite slab or shell floors of concrete – corrugated steel plate. The effect of interface between steel and concrete can be idealized by special finite elements. In contrast, these interface elements have characteristics that can not be used in the classical methods⁽¹⁰⁾. Therefore, the composite concrete – corrugated steel shell can be represented here for analysis into (concrete, arched corrugated steel plate, reinforced steel mesh, interface) elements in order to be idealized by a computer program as the next step of calculation. The computer program used here is called ANSYS (from taking the first characters of the words ANalysis SYStem).

- **Concrete element representation:**

An eight - node solid brick element is used to model the concrete. The solid element has eight nodes with three degrees of freedom at each

node, translations in the nodal x, y, and z - directions.

- **Steel bar element representation:**

Reinforced mesh of 4mm in diameter and (100 x 100) mm in opening is used for reinforcing the concrete over the corrugated steel shell. There are three common types of representation for reinforcing steel bars inside concrete⁽¹⁰⁾.

- **Corrugated steel plate representation:**

A four – node nonlinear shell element with five degrees of freedom at each node is used. Three degrees of freedom belong to local displacements (translations) in (x, y and z) and the remaining two degrees of freedom refer to rotations of the normal x and y coordinates⁽¹⁰⁾.

- **Flexible-Flexible contact:**

Both contact and target surfaces are associated with deformable bodies. This is adopted in the present study. Contact problem analyses are based on Hertz contact stress theory, which has approximation on two counts. First the geometry of a general curved surface is described by quadratic terms only and second, the two bodies, at least one of which must have a curved surface, are taken to deform as though they were elastic half – spaces⁽¹¹⁻¹³⁾.

The Geometry of Designed Shape:

As a next step of applying the element types and their material properties, the dimensions of a full – size testing specimen 12m x6m x 0.52 m are taken into consideration. This specimen has a large number of elements reaching (681 696 elements). So it is better to simplify

the specimen into strips by benefiting from the symmetry of the structure and load in order to reduce the size of the specimen. So, a strip of this specimen is considered with smaller dimensions. By using this procedure, the strip has dimensions (0.5 m X 3 m X 0.52 m) with (14202 elements) as prepared in Table (4) and Figure (4).

Displacement assumption:

The displacements at each node of the element lying at a supported face are equal to zero (U_x, U_y, U_z) in x, y and z -directions respectively. The moments M_x and M_y at the discussing nodes are equal to zero because of the **tie bar** working as balancing axial force against the rotation moments.

At each remaining face of symmetry, the displacements in x-direction are equal to zero and released free at z-direction, as shown in Figure (5).

Results And Analysis

In order to have the whole idea about the results of the tested strip, four cases of loading are considered and for each the load - deflection curve is drawn. These cases of loading are as follows:

§ First Case

In this case a uniformly applied load on full flat surface is considered. Zeman & Co Gesellschaft, 2004⁽⁵⁾ had tested the trapezoidal arched composite system [Figure (6)]

§ Second Case

A uniformly applied line load at the strip in the middle of flat surface is considered Figure (7). This line load application, of length (3m) of the strip.

§ Third Case

In this case a uniform line load is applied only at the exterior flat (symmetry) nodes as shown in Figure (8). The length of the load is (0.50m).

§ Fourth Case

Briefly, the applied load is represented as a single load located at the middle node of exterior free (symmetry) edge, Figure (9).

Conclusions

1. Frequently, as it is denoted, the first crack happens at different loads according to the nature of applied load and its distribution and contribution. First crack appearance depends also on the physical properties of the material especially on the tensile strain characteristics (Saint – Venant theory of brittle materials in which failure criterion is related to the maximum tensile strain of the material and its behavior under loading after first crack and its ability for a large displacement of brittle behavior).
2. After the first crack, more cracks are developed and in all cases, the maximum deflection occurs at most critical point " located in the middle node of crown edge on flat surface and this deflection is (4.65mm) at load (6.46 kN/m²) of load 1st case.
3. It is found that there is only one concrete element that has been crushed for the case of a single load at a node at crown edge (symmetry edge) but after this, there is no full crushing (or failure) of the specimen in this study. This is because the computer program stops after first crush of

element. There are several modern studies trying to make the analysis continue if one of the elements fails by freezing the action of failing element and other subsequent failing elements until the full structure fails as a mechanism.

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Table (1) Uniaxial stress – strain relationship of concrete adopt program ($f'_c = 20$ MPa)

Point Number	Strain (mm/mm)	Stress (N/mm ²)
1	-0.00026	-5.06
2	-0.00060	-10.45
3	-0.00095	-14.24
4	-0.00130	-16.5
5	-0.00173	-19.85

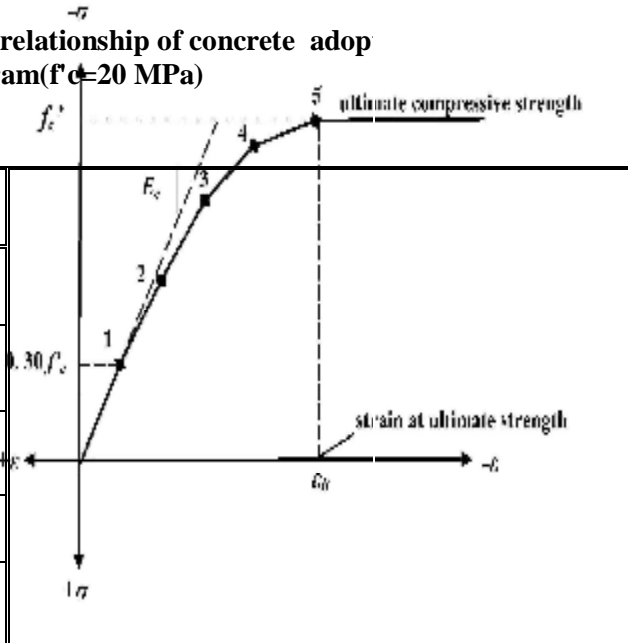


Table (2) Uniaxial stress –strain relationship of corrugated steel plate adopted in ANSYS program

Point Number	Strain (mm/mm)	Stress (N/mm ²)
1	0.001	280
0	0	0.00
2	- 0.001	-280

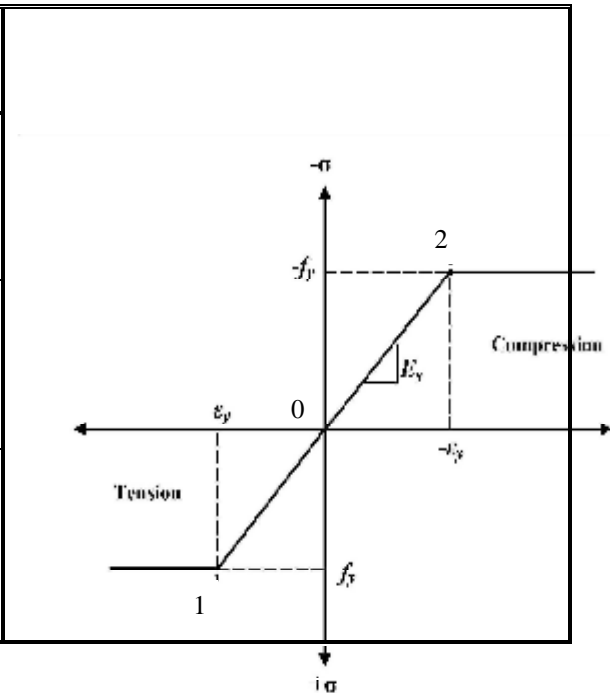


Table (3) Uniaxial stress –strain relationship of steel bar adopted in ANSYS program

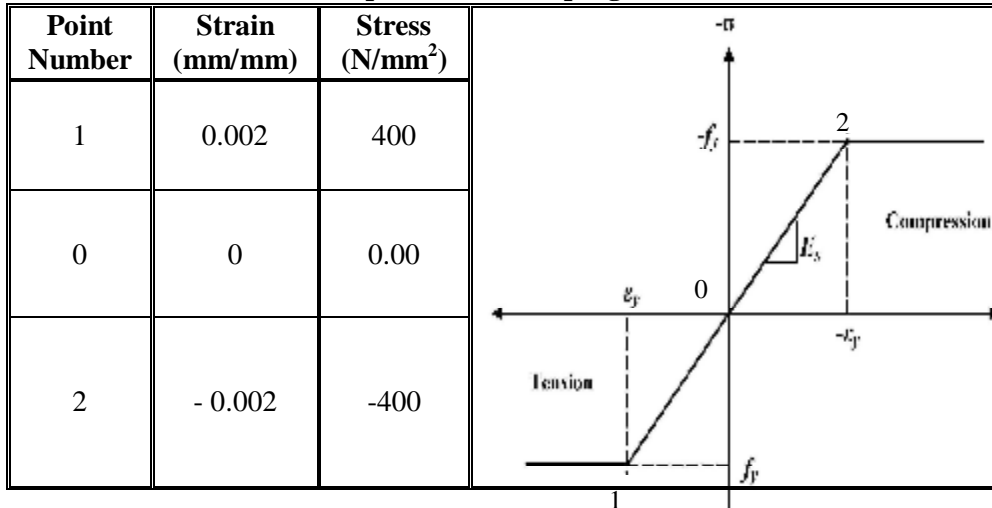


Table (4) Properties of material adopted in the tested Strip by ANSYS program

Physical properties	Concrete	Corrugated Steel plate	Steel bar
Density (kN/m ³)-[ρ]	23.8	78.60	78.60
Initial modulus of elasticity (N/mm ²)-[E _x]	19500	280 X10 ³	200 X10 ³
Modulus of Rigidity (N/mm ²)-[G]	0	75 X10 ³	75 X10 ³
Strength of Material in compression (N/mm ²)	As shown in Table (1)	As shown in Table (2)	As shown in Table (3)
Strength of Material in tension (N/mm ²)	2.6	280	400
Poisson's ratio-[ν]	0.2	0.32	0.32
Shear retention factor -[β]	0.2		
Friction coefficient-[μ]	0.7 (between concrete and steel plate)		

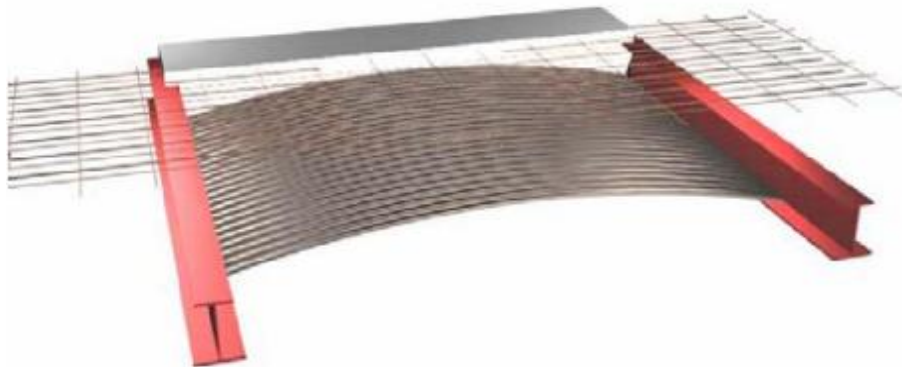


Figure (1) Representation of the principles of construction
/topview/ (Zeman & Co Gesellschaft, 2004⁽⁵⁾)

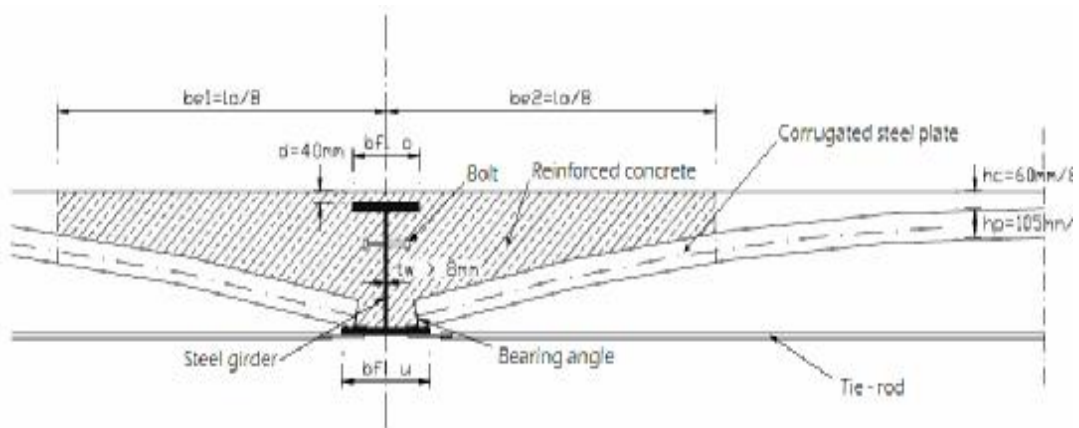


Figure (2) Representation of interior details of arch deck
component (Zeman & Co Gesellschaft, 2004⁽⁵⁾)

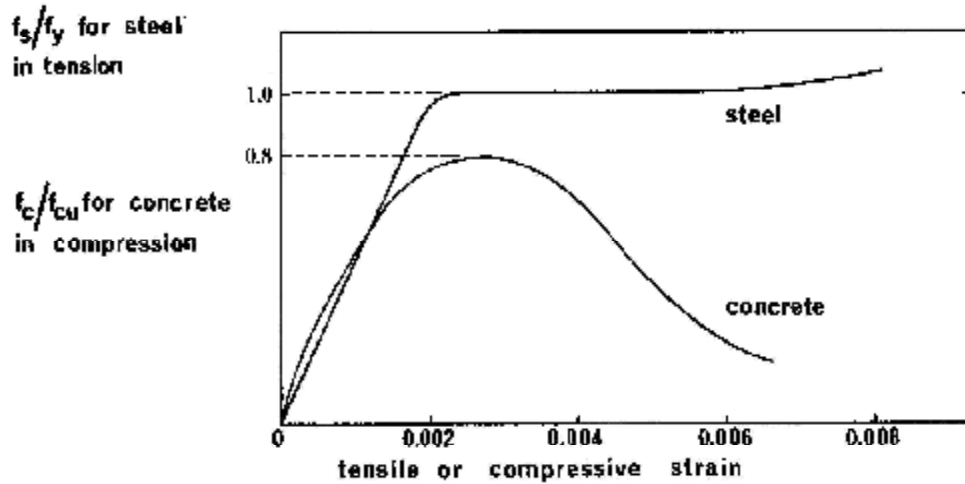


Figure (3) Stress – strain curve for concrete and structural steel (stresses are in ratio of ultimate strength), Johnson,1994⁽⁸⁾

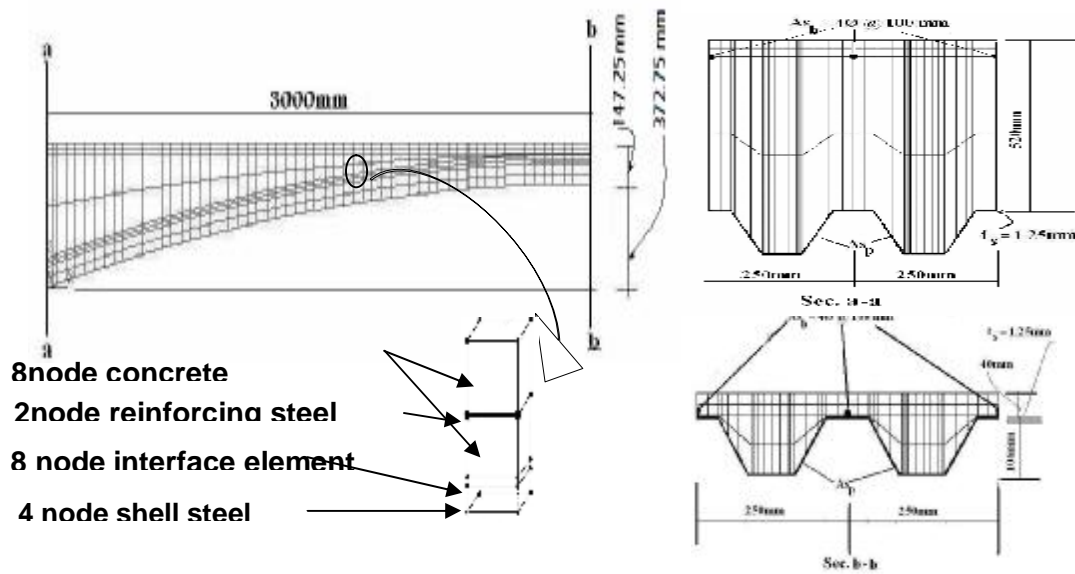


Figure (4) Details of the tested strip of the cylindrical composite shell(3x0.5x 0.52)m

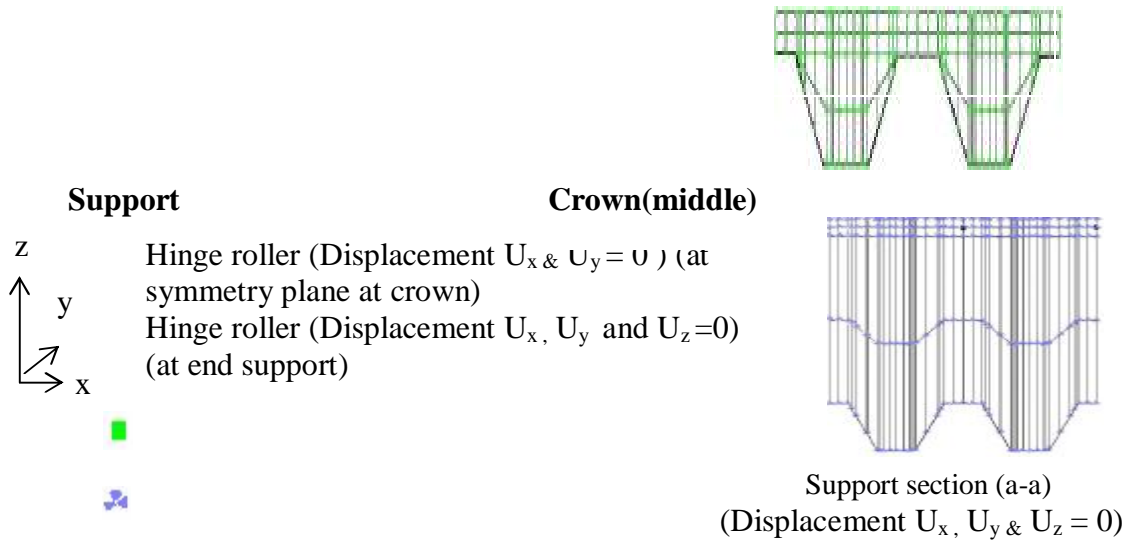
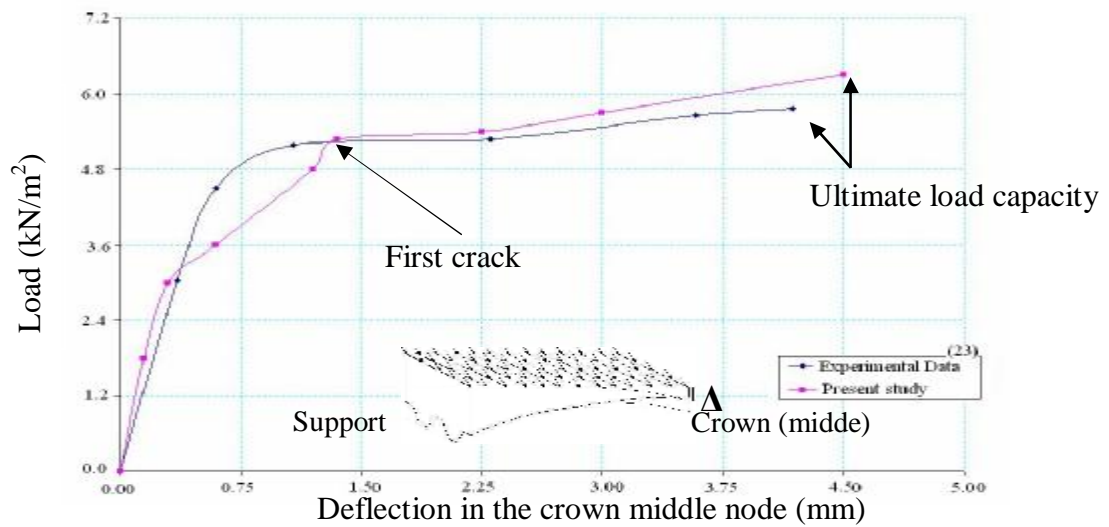
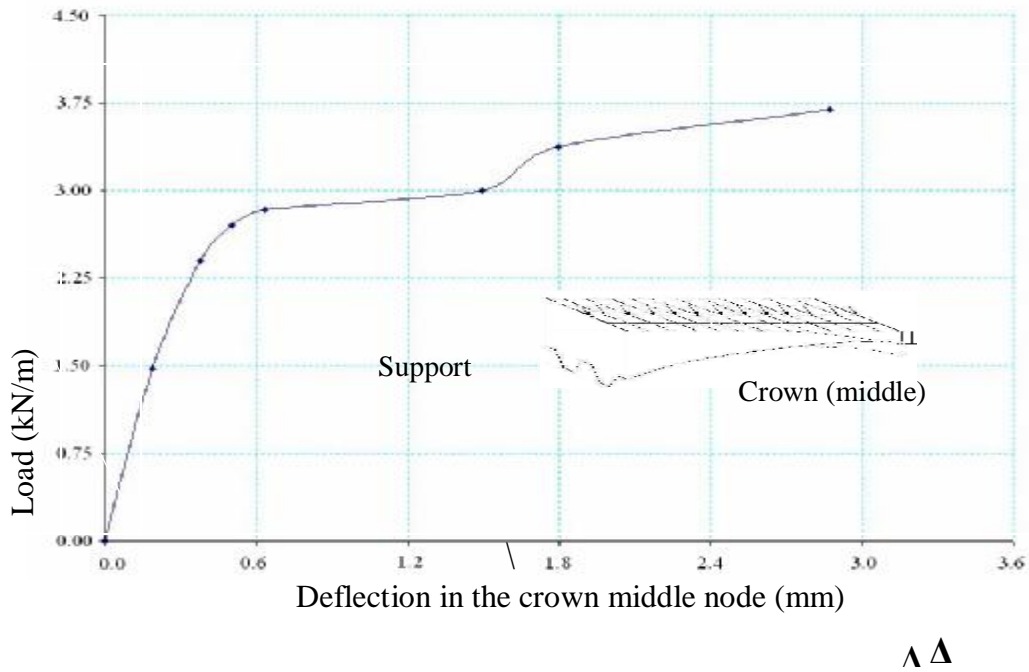
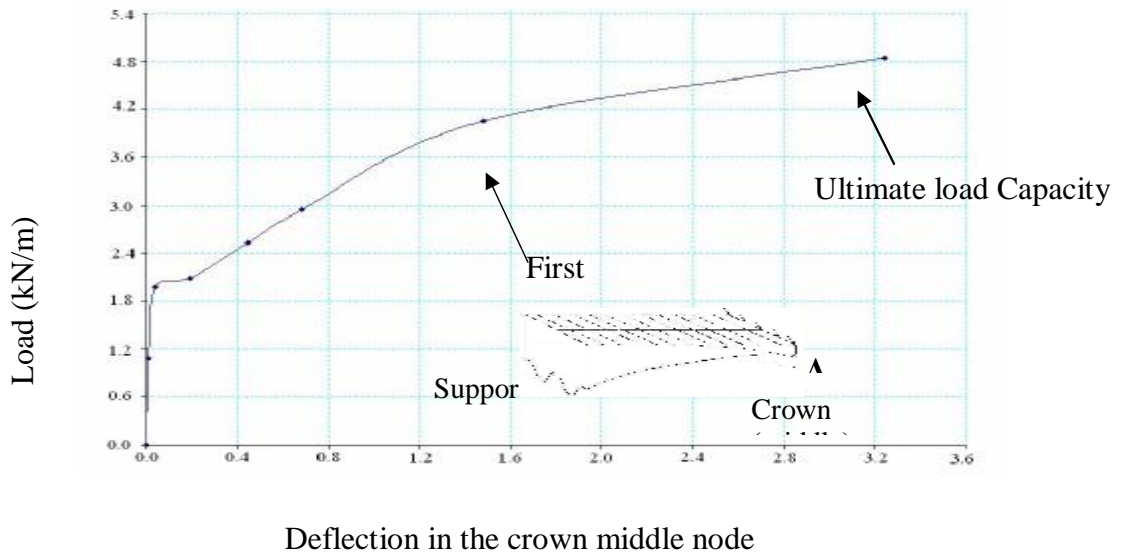


Figure (5) Boundary conditions of the tested strip of cylindrical composite shell

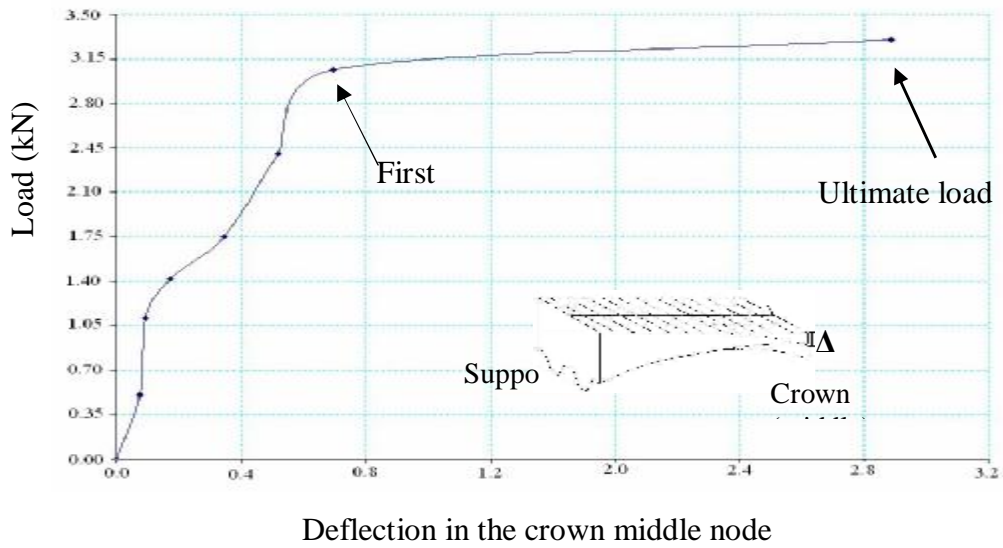




Figure(7) Load-deflection relation for line loading along the middle of strip flat surface (2nd case)



Figure(8) Load - deflection relation for applying uniform load only at exterior flat nodes (3rd case)



Figure(9) Load – deflection relation for single load located at middle node of exterior free edge (4th case)