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Thin RC Shell-Slab Roofing System with Steel Rod Connections

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Abstract

An innovated structural system, namely the **S**hell-**S**lab **R**oofing **S**ystem (**SSRS**) of precast thin reinforced concrete cylindrical shell and flat slab has been fabricated as a roof segmental unit. The flat slab rests on the cylindrical shell at the crown and also connected to the shell by steel rod connections at each side. Steel plate strips are fixed on the bottom surface of the slab and on the top and the bottom surfaces of the shell as external tensile and shear steel reinforcement to prevent punching shear around the steel rod connections. The ratio of the shell height to the chord length was (0.1). The structural behavior of the roof system had been investigated under uniformly distributed static load. Experimental work was carried out by fabrication of six complete segments with scale-down simulation factor equal to (0.25). The vertical deflections had been observed at selected positions on the models. A water/cement ratio of (0.5) combined with a cement: sand ratio of (1:2) had been employed. The influence of certain experimental parameters had been studied. The model with only twelve rod connections and minimum reinforcement volume ratio was adequate to resist the live loads for buildings with large span roofing. The investigation showed that the combined unit of thin concrete shell and flat slab with embedded small diameter steel reinforcement was suitable for construction of such roofing system as large span structures with lower ratio of shell height to chord length (h/c) equal to (0.1).

Keywords: Cylindrical Shells, Flat Slab, Roofs, Concrete Shells, Rod Connections, Steel Plate Strip.

منظومة تسقيف قشرة - بلاطة خرسانية مع روابط قضبان فولاذية

الخلاصة

تم أبتداع منظومة جديدة من أنظمة التسقيف اطلق عليها تسمية منظومة تسقيف القشرة والبلاطة وهي عبارة عن وحدات جاهزة من الخرسانة المسلحة ذات السمك القليل تتكون من بلاطة مستوية وقشرة أسطوانية واطئة الأرتفاع لتشكيل وحدة تسقيف. تسسند البلاطه على القشرة عند المنتصف وترتبط معها من الجانبين بواسطة روابط قضبان فولاذية تنقل الأحمال من البلاطة الى القشرة. تم تثبيت شرائح حديدية تحت البلاطة وفوق وتحت القشرة الأسطوانية كحديد تسليح خارجي ولمقاومة قوى القص الثنائي التي قد تحدث حول روابط القضبان الفولاذية. تم استعمال نسبة أرتفاع الى طول وتر القشرة تساوي (0.1). تم تقصي التصرف الأنشائي لوحدات التسقيف تحت حمل ستاسيكي منتظم مع دراسة تأثير عدة متغيرات عملية. تضمن البرنامج العملي أنشاء ست وحدات تسقيف متكاملة بأستخدام معامل تصغير يساوي (0.25) وبأعتماد نسبة مزج الماء الى الأسمنت (0.5) ومزج الأسمنت الى الرمل مساوية الى (1:2) وجرى اختبار

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الوحدات لقياس الأزاحات العمودية والأنفعالات على السطح في عدة مواضع مختارة. تبـــين أن المنظومة التي تحتوي أقل نسبة لحديد التسليح الداخلي وعدد روابط القضبان الفولاذية (12) تفي لمقاومة الأحمال الحية للأبنية ذات الفضاءات الواسعة واثبتت الدراسة أمكانية أستخدام مثل هذا النوع من التسقيف للفضاءات الواسعة والأبنية التقليدية بنسبة تحدب **(h/c)** واطئة تساوي **(0.1)**.

Introduction

Recently an increasing number of reinforced concrete shell structures, such as domes, auditoriums, silos, reactor containers and aesthetic roofs have been built. The combination of three-dimensional geometrical complexities and the loading conditions of shell structures, as well as the three- dimensional nonlinear behavior of reinforced concrete are still the big challenge for construction of such structures [1]. The increased use of thin shells has led to an increased understanding of their behavior through field observations, laboratory tests and mathematical refinement of analytical procedures. Classical shells have a thickness-to-radius ratio of 1:50; eggshells can have a thickness-to-radius ratio of 1:100; modern concrete shell domes can be built to a significantly smaller ratio of 1:800. Constructed with small quantities of simple, inexpensive, low-tech concrete and wire mesh, these structures are safe as well as beautiful [2]. A shell is primarily required as a roof to cover large areas with minimum obstructions and in a most economical way of material saving. The main difference between a shell and any other form of roof structures is the inherent strength of the shell due to its shape, its complete reliance for strength on its thin skin and its low materials to surface ratio. The applications of shell structures as compression members are still limited in spite of possessing the inherent compressive resistance. Most of the constructed shell roofs resist the loads which come from their own weight only far away from the service load capacity. The studies which have been focused on using shells (especially circular domes) in the building foundations enhance the idea of using the shells as bearing roofs. A thin shell may be described as a structure in which loads are transferred primarily by direct (membrane) stresses, with relatively small or localized bending stresses[3]. A shell which is formed by translating a curved line along a straight longitudinal axis and which spans longitudinally between supporting diaphragms is termed a cylindrical shell.

A new innovated structural system, namely the **S**hell-**S**lab **R**oofing **S**ystem (SSRS) of precast thin reinforced concrete with steel plate strips and short steel rod connections has been fabricated as a roof segmental unit. The (SSRS) segment is formed by connecting the top flat slab to the shallow cylindrical shell by short steel screwed rods with longitudinal and transverse thin steel plate strips which serve as the external tensile and shear steel reinforcement. The steel rod connections transfer the loads from the slab to the shell and contribute with supports to confine the transverse displacements in the cylindrical shell. The cylindrical shell is supported by two monolithically cast straight edge beams of rectangular section on the sides. The design of the molds considers that the concrete units have forty holes on each shell and slab after removing the units from the molds. Steel rods penetrate the shell and the slab through holes and are fixed by washers and nuts at top and bottom of each the shell and the slab. Longitudinal and transverse steel strips are added at the bottom of the slab and on the top and on the bottom of the shell. Figure (1) illustrates the proposed model of the shell-slab roof system (SSRS). The main objective of this research is to investigate the behavior of the shell-slab roof system (SSRS) under uniformly distributed static load. Experimental work will be carried out to assess the capabilities of both the thin concrete shell and the thin concrete slab in carrying the loads and the probable modes (or types) of failure. Six complete segments will be erected with scale-down simulation to study the influence of the experimental parameters which include the following:

1. Steel reinforcement content in the shell and the slab.
2. Numbers of steel rod connections and spacing between them.
3. Adding external steel plate strips on the top surface of the shell and on the bottom surface of the slab in the y-direction.
4. Adding external steel plate strips on the top and the bottom surfaces of the shell in the x-direction.

Advantages and applications

The main advantages of the (SSRS) are summarized as follows:

1. Covering large areas of column-free space with material minimization.
2. The utility in using the system as a traditional floor by converting the cylindrical roof to a flat floor.
3. The usefulness of adding another floor area to the building and widening the possibility of constructing multi-story buildings by this type of roof system.
4. Mass factory production of the SSRS units of standard sizes and curvatures.
5. Heat and sound insulation and providing a proper space for electro-mechanical services between the shell and the slab.

The SSRS can be used in the applications of the long span roofs, tunnels, arch bridges and architectural entrances.

Background

Teng et al. (2004) [4] presented a steel-concrete composite shell roof (Comshell roof), for enclosing large spaces. A Comshell roof was formed by pouring concrete on a thin stiffened steel base shell which serves as both the permanent formwork and the tensile steel reinforcement. The thin steel shell, constructed by bolting together modular units consisting of a base plate with surrounding edge plates, is a steel shell with thin stiffeners in both directions. A two-stage construction process aimed at minimizing the sheeting thickness and the number of temporary supports during construction had also been presented. In stage1, concrete was cast over selected rows to form steel-concrete composite arches to stiffen the base shell for the casting of the rest of the concrete. During stage 1, the buckling behavior of individual bolted steel arches under wet concrete loading was of critical importance. During stage 2 casting of concrete, buckling of the bolted steel shell segment between two composite arches and buckling of the composite arches control the strength of the structure. After construction, the overall buckling of the roof under gravity loading was believed to be the most important failure mode. For a Comshell roof in service, unilateral buckling of the base plate was another likely failure mode and had been observed in the model Comshell roof tests. An experimental program involving the tests of 3 laboratory model base shells was planned and completed to study this buckling problem. In the test of the first and second specimen, it was found that local buckling of the stiffeners and base plates that occurred first, followed by stable post-buckling deformations. Final failure of the shell occurred by overall buckling. On the other hand, in the test of the third specimen, it was found that overall buckling occurred suddenly without an accumulation of the local buckling. Steel base arch with long connection bolts and failure mode of a composite arch are shown in Figures (2) and (3) respectively.

Zeman and **Co Gesellschaft mbH** [5] proposed an arch deck system as a composite flooring system for building and industrial construction. It links the concept of the Slim Floor Ceiling (composite floors with an integrated embedded steel girder paired with lower overall floor thickness and integrated fire protection) to the concept of the self-supporting trapezoidal arched sheet. The trapezoidal arched composite flooring system consists of steel girders placed with a spacing of approximately (4000) to (6000) mm and trapezoidal arched sheet elements resting on their bottom flanges in the fields in between. They serve as bearing shuttering for the concrete on the ceiling. The final result is a concrete arched ceiling. Thereby a continuous reinforced concrete slab of tapered cross-section, beside the steel girders, simultaneously serves as top flange of the composite beams. Figures (4) and (5) show the top and the bottom representation of the construction principle of the arch deck system respectively. The extremely tapered shape of the floor slab results in a minimized bending moment of the span. Thus an overall sheet thickness of (60) to (80 mm) on top of the trapezoidal arched steel plate and the required minimum reinforcement for compensating the span moments are sufficient. On the other hand an adequately large concrete cross section is available for the moment at the support. Compressive forces of the concrete are compensated by direct attachment of the steel girder web, tensile forces originating at the upper part of the sheets are compensated by a corresponding reinforcement. Due to the relatively large lever arm, minimum reinforcement is sufficient in this case as well. Compared to conventional floor systems the advantages of the arch deck system had proven to prevail, particularly with increasing load capacity ($P \geq 5$ kN/m^2).

Extension to the above-mentioned work, an extensive investigation is carried out on an innovated roofing system consisting of thin shallow cylindrical reinforced concrete shell and flat reinforced concrete slab connected by short steel rod connections and fixed at edges by beams. The load-deflection curves up to the ultimate load are plotted from which serveral conclusions are obtained. This roofing system is found suitable for practical purposes (using lower rise to chord length ratio of 0.1).

Experimental program

The experimental work considered in this study is based on preparing six complete precast units of shell-slab roofing system (SSRS) by scale down to a factor equal to 0.25. The geometry of the final shape of the model is drawn in Figure (6). The experimental variables are detailed in the Table (1). The shell model used in the present work was a segment of a short cylindrical roof. The width of the segment was (400mm), the chord length was (1500mm), the shell height was (150mm) and the shell thickness was (30mm). The shell is supported on a rectangular edge beam on each side. The dimensions of the beam were (400mm) in length, (100mm) in width and (60mm) in height. The total span length of the shell with edge beams becomes (1700mm). The dimensions of the slab model should depend on the dimensions of the shell model as the shell and the slab represent an integral roof unit. Hence, the width of the slab model was (400mm), the span length was (1700mm) and the slab thickness was also (30mm). Twenty small circular holes with diameter of (12mm) were provided in each side of both the shell and the slab. The spacing between any two holes along (x) or (y) direction was (120mm). The reinforcement of the models had been carried out by using layers of welded meshes of plain round steel bars with diameter of (4mm) and (50mm) spacing in each direction. These layers are easy to be cut, handled and curved or bent. A water/cement ratio of (0.5) combined with a cement/sand ratio of (1:2) had been employed. Ordinary Portland cement and natural yellow sand passing ASTM No. 4 (4.76 mm) sieve and ordinary tap water were used throughout the investigation. Cement mortar reinforced with small diameter plain round bars had been used in the present work. Small diameter plain round bars are used for reinforcement because of their identical stress-strain characteristics to the prototype bars [6]. For accurate representation of a prototype structure, the stress-strain relationship of the model and the prototype must be similar and the modulus of elasticity should be sufficiently low, so that the strains and displacements could be measured accurately. From the above conditions, the reinforced cement mortar attains the requirements which must be fulfilled by the model materials.

The molds were oiled at corners and short plastic pipes were used to facilitate the separating and removing the casting units and taking out the models. The connection between the shell and the slab was accomplished mechanically. Additional steel strips were fixed on the top of the shell and on the bottom of the slab in y-direction. Also other strips were fixed on the top and bottom of the shell in x-direction over the strips which were fixed in y-direction. The width of each strip was (40mm) and the thickness was (2mm). Each strip in any direction was drilled by the same diameter of the holes in the concrete shell and slab. Screwed circular steel rods with diameter of (11.8mm) were used to pass through the circular holes in the shell, slab and steel strips. The screwed rods penetrate the precast concrete components and the steel strips and they were tied by washers and nuts at the top and the bottom of both the shell and the slab in order to fix the steel strips with the precast concrete components on one hand, and to connect the shell with the slab as one roof unit on the other hand. To provide fixed supports at the edge beams of the shell, a supporting steel frame consisting of two main steel beams of (H) section with dimensions (120*120*8mm) were placed in parallel and were welded with one transverse tie strip of (6mm) thickness at each beam end. Three additional transverse tie strips were welded at certain distances to contribute with the end strips for preventing the movement in the longitudinal direction of the steel beams and for fixing the dial gauges during the loading test. The measurement of displacements in the models was carried out by dial gauges with sensitivity of (1E-3 mm) and with (25 mm) as a full range. Selected dots were marked on the bottom surface of the shell and then demec points were fixed by epoxy resins. Figure (9) illustrates the positions of the demec points on the model. Most of the model analyses of shell or slab roofs are done by considering uniformly distributed loads by placing small weights on the surface or by applying a series of point loads or by using a pressure loading [7]. The first technique was tried on the first model and then retested with the other five models which were tested by using the loading apparatus in the Building and Construction Laboratory of the University of Technology (Baghdad, Iraq). The applied load by the contact bearing plate of the loading apparatus was converted to a uniformly distributed load on the whole horizontal top surface of the model by using steel sections arranged along the length and width of the model with packs of sand bags to ensure good distribution as shown in Figure (10). Each (1kN) of apparatus reading as a concentrated load was equal to (1.47E-3 N/mm^2) as a distributed surface pressure. The specimen results of the measured displacements and strains for model (U1) are in Table (2). The sets of figures from (11) to (16) show the connecting of the models, manner of loading, and the models after failure.

Load-Deflection Results

The experimental results compared at three selected positions up to failure according to the angle of curvature. The (-) sign indicates the downward displacements and compressive stresses or strains and the (+) means the upward displacements and tensile stresses or strains. The load values on the Figures represent the reading values of the loading test apparatus (total load) at the instant of deflection reading. Figure (17) shows that the vertical displacements were always downwards at Øc=0° for all models while they were downwards at Øc=10° for all models except U5 and U6 as in the Figure (18). In the Figure (19), at Øc=19° near the edge beam, the displacements decrease and varies from upwards to downwards for the models U1, U2, and U3. When the number of steel rods increases and the spacing between them in the y-direction decreases as in the models U4, the reversing points at the curve disappear and the deflections were always downwards. By adding the external steel strips on the bottom surface of the flat slab and on the top and bottom surfaces of the cylindrical shell as in the models U5 and U6, the deflections decrease with increasing stiffness of the structure. The disappearance of the reversing points on the load-deflection curves means decreasing in the negative moments by decreasing the spacing between rod connections. The failure mode was crushing of the concrete around the steel rod connections for the models without the external steel strips. The mode of failure changes to become a yield line at the connection between the cylindrical shell and the edge beam for the models with external steel strips. This means that the external steel strips confine the section of thin shell and transfer part of membrane stresses to the edge beam with increase of the ultimate load capacity.

The effect of the studied parameters on the results and the behavior can be summarized as follows:

1. The increase of the volume ratio of steel reinforcement causes an increase in the ultimate load capacity and decrease in the maximum vertical deflection (at the same load step value).
2. With the same volume ratio of steel reinforcement, the increase of the steel rod connections also increases the ultimate load capacity and reduces the maximum vertical deflection.
3. With the same volume ratio of steel reinforcement and the number of the rod connections, the ultimate load capacity increases and the maximum vertical deflection decreases with adding external steel strips on the bottom surface of the slab and on the top and bottom surfaces of the shell.
4. The volume ratio of reinforcement has the greatest effect on the increase of the ultimate load capacity, as observed in model (U3), while adding external steel strips in two directions has the greatest influence on restraining the maximum vertical deflection as found in model (U6).

Conclusions

From the experimental results, the following conclusions may be drawn:

1. The investigation shows that the combined unit of thin concrete cylindrical shell and flat slab with embedded small diameter steel reinforcement is found suitable for construction of such roofing system for large span structures.
2. The used shell-slab connection technique provides stability and consistency for the roofing system under load application up to failure.
3. The use of lower ratio of crown height to chord length (0.1) for the cylindrical shell was found suitable for traditional roofing and it is out of buckling load limit.
4. The failure modes were either by crushing of the concrete in the stress concentrated zones around the circular holes for the models without external steel strips or by yield lines between the cylindrical shell and the edge beams for the models with external steel strips.
5. The feasibility of converting the arch (vault) floor to a traditional plane roof gives the ability to construct multi-story buildings by using this roofing system.
6. Model (U1) with only twelve rod connections and minimum reinforcement volume ratio was

found adequate to resist the live loads for building with large span roofing

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Table (1) Experimental considered parameters

Models	Steel Reinforcement (r)		Steel rod connections			Steel Strips		
						shell		Slab
	Shell	Slab	No.	Spacing X (mm)	Spacing Y (mm)	Along X	Along Y	Along Y
U1	0.01801	0.01801	12*	360	240	_	_	_
U2	0.02701	0.02701	12*	360	240	_	_	_
U3	0.03602	0.03602	12*	360	240	_	_	_
U4	0.02701	0.02701	20**	120,360	240	_	_	_
U5	0.02701	0.02701	20**	120,360	240	_	Ö	Ö
U6	0.02701	0.02701	20**	120,360	240	Ö	Ö	Ö

*The Distribution of rod connections is shown in Figure (7).
** The Distribution of rod connections is shown in Figure (8).

Table (2) Experimental results for model (U1)

Load (kN)	Angle of curvature								
	Øc=0°			Øc=10°			Øc=19°		
	Uz (mm)	Strains		Uz (mm)	Strains		Uz (mm)	Strains	
		x	y		x	y		x	y
0	0	0	0	0	0	0	0	0	0
5	-0.082	1E-05	1E-05	-0.036	-1E-05	-1E-05	-0.001	-2E-05	-3E-05
10	-0.152	3E-05	3E-05	-0.078	-3E-05	-2E-05	-0.004	-3E-05	-5E-05
15	-0.253	5E-05	6E-05	-0.102	-4E-05	-3E-05	-0.012	-5E-05	-7E-05
20*	-0.364	7E-05	8E-05	-0.168	-5E-05	-5E-05	-0.019	-6E-05	-8E-05
25	-0.513	9E-05	1.2E-04	-0.268	-7E-05	-7E-05	-0.022	-6E-05	-1.3E-04
30	-0.786	1.2E-04	1.4E-04	-0.298	-1E-04	-8E-05	-0.026	-7E-05	-1.6E-04
35	-0.941	1.6E-04	1.7E-04	-0.354	-1.6E-04	-1.2E-04	-0.010	-9E-05	-1.8E-04
40	-1.132	1.7E-04	2.1E-04	-0.384	-1.9E-04	-1.5E-04	0.002	-1.2E-04	-2E-04
45	-1.354	1.7E-04	4.8E-04	-0.422	-2.4E-04	-1.7E-04	0.015	-1.3E-04	-2.2E-04
50	-1.487	1.8E-04	5.3E-04	-0.541	-2.6E-04	-1.8E-04	0.023	-1.5E-04	-2.5E-04
55	-1.522	2E-04	6.6E-04	-0.685	-3E-04	-2E-04	0.045	-1.7E-04	-2.8E-04

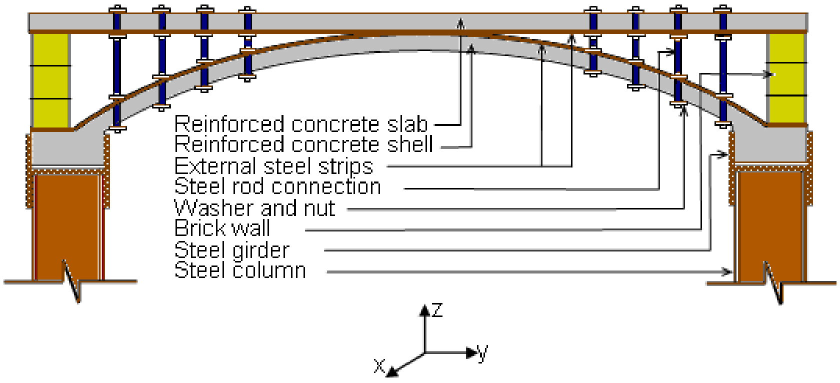

Figure (1) Proposed shell-slab roof model

Figure (2) Steel base arch with long connection bolts [4]

Figure (3) Failure mode of a composite arch [4]

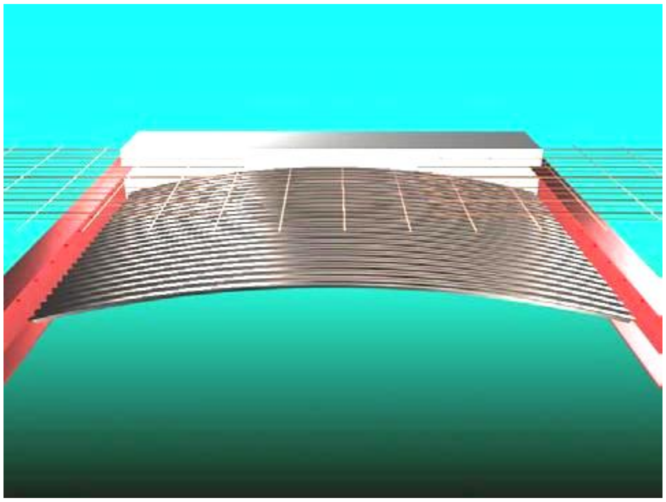

Figure (4) The top representation of the construction principle [5]

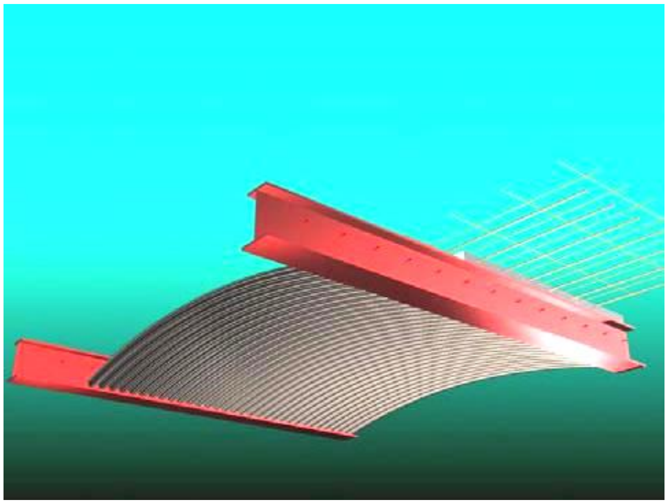

Figure (5) The bottom representation of the construction principle [5]

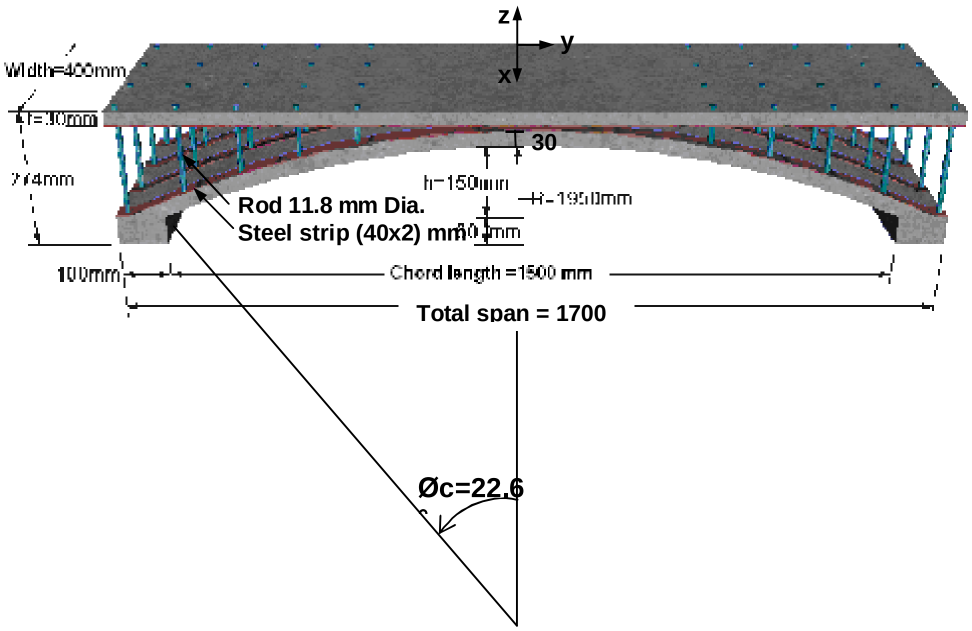

Figure (6) Geometry of the final shape of the unit model

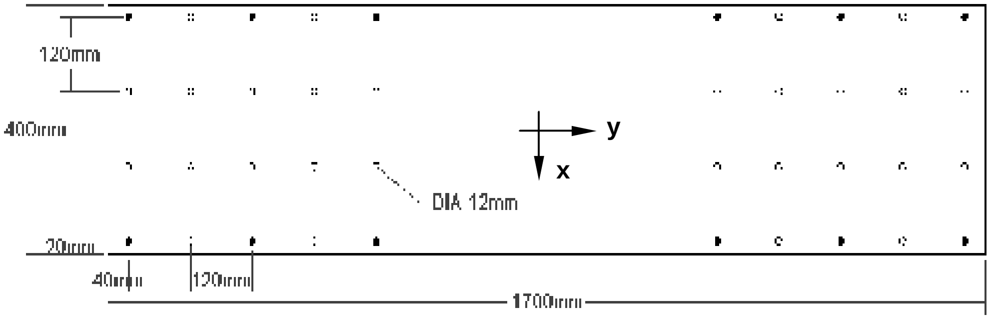

Figure (7) Solid circles representing the positions of rod connections (U1, U2 and U3)

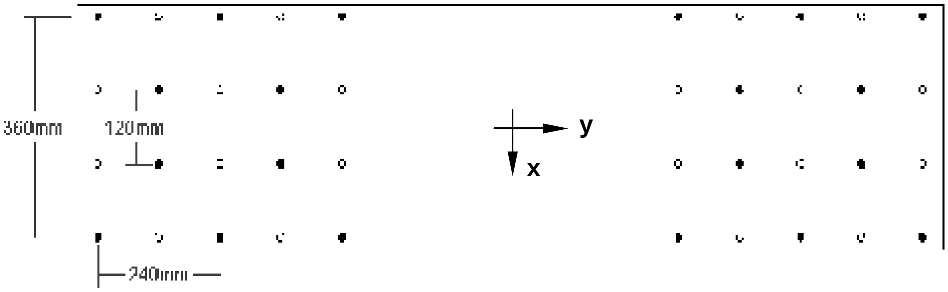

Figure (8) Solid circles representing the positions of rod connections (U4, U5 and U6)

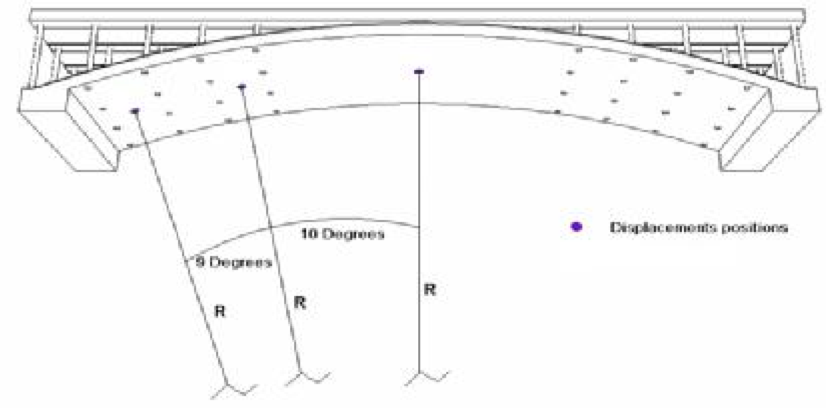

Figure (9) Positions of the demec points on the model

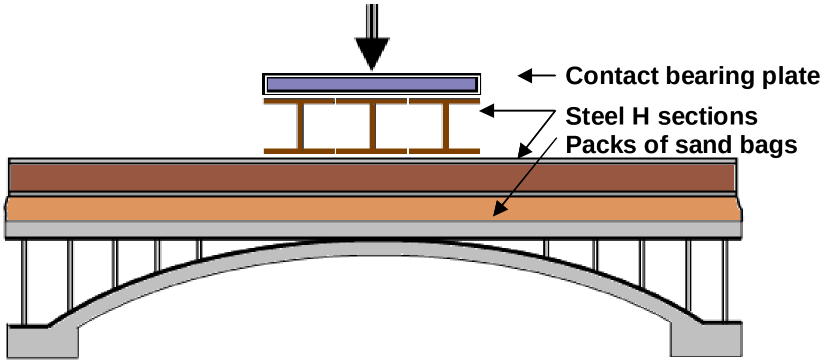

Figure (10) Conversion load

*** First crack**

Figures set (11) Model (U1)

Figures set (12) Model (U2)

Figures set (13) Model (U3)

Figures set (14) Model (U4)

Figures set (15) Model (U5)

Figures set (16) Model (U6)

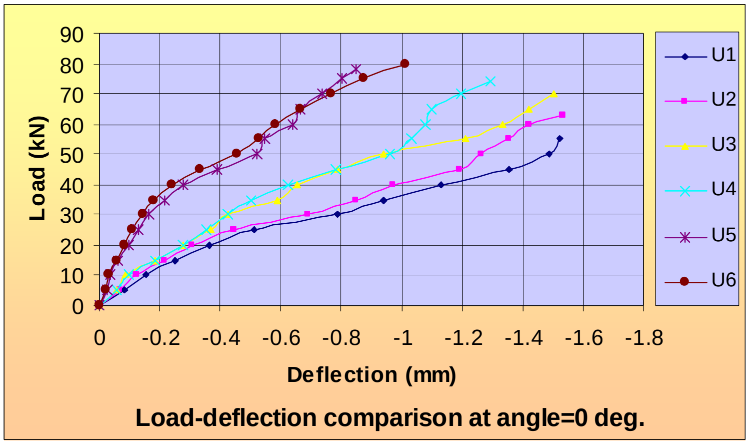

Figure (17)

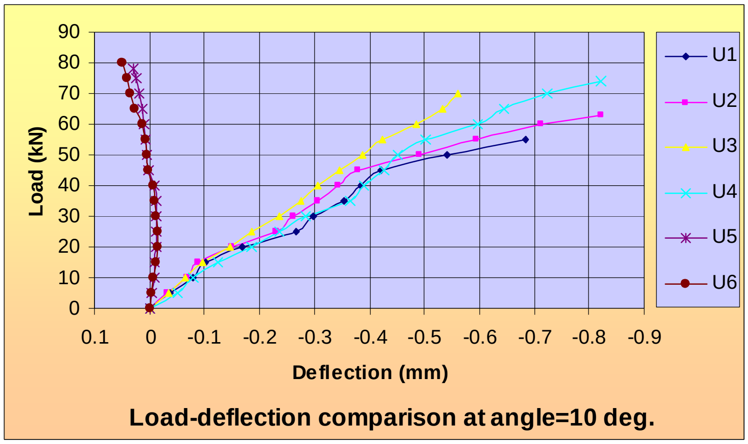

Figure (18)

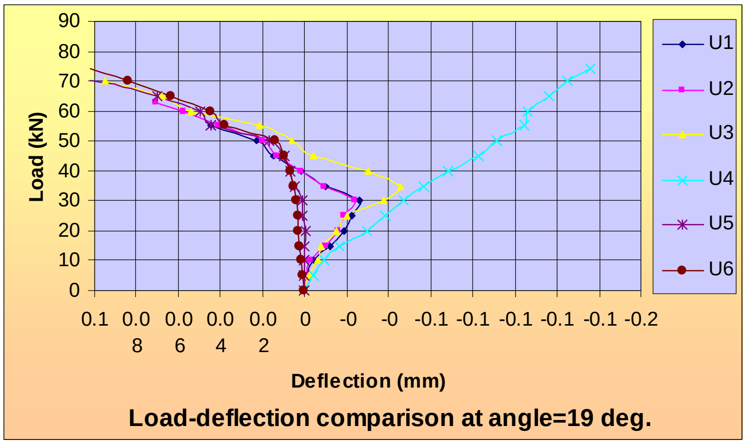

Figure (19)