

Experimental Investigation of Composite Steel-Concrete Arches

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ABSTRACT

This research is concerned with behavior of composite steel-concrete arches under static load. For this purpose, eight models of composite steel-concrete arches are fabricated as test specimens. According to their supporting systems, the eight fabricated specimens are equally divided into Hinge-Roller and Hinge-Hinge supported arches in which varied numbers of shear connectors are used to investigate the effects of support conditions and degree of shear connection on the behavior of the composite arches. The specimens are tested under monotonically increasing point load applied on their crowns (on the top of concrete slabs).

The mechanical properties of the used materials are determined by laboratory tests. Push-out tests on three specimens, fabricated for this purpose, are also carried out to determine the properties of the stud shear connectors.

It is concluded that increasing the number of connectors tends to increase the ultimate load capacity and decrease both displacement and slip in the composite arches. This trend is considerably satisfied when the horizontal movements of supports are constrained (Hinge-Hinge supported arches).

Keywords: Composite Construction, Arches, Curving Process, Finite Elements.

دراسة عملية للأقواس المركبة الفولاذية- الخرسانية

الخلاصة

إهتم البحث الحالي بالسلوك الإنشائي للأقواس المركبة تحت تأثير الأحمال الساكنة. حيث تم تصنيع ثمانية أقواس فولاذية-خرسانية مركبة كنماذج للفحص. وقد تم تقسيم النماذج المصنعة الثمانية بالتساوي إلى: أقواس ذات إسناد مفصل- متدرجة وأقواس ذات إسناد مفصل- مفصل وباستخدام أعداد متباينة من رباطات القص في كل من المجموعتين وذلك لدراسة تأثير ظروف الإسناد ودرجة ترابط القص على سلوك هذه الأقواس المركبة. وقد تم فحص هذه النماذج تحت تأثير حمل مركز متزايد بانتظام تم تسليطه على قمة النموذج (على سطح البلاطة الخرسانية).

الخصائص الميكانيكية للمواد المستخدمة تم تحديدها بالفحص المختبري كما تم إجراء فحوصات الدفع-خارجاً على ثلاث نماذج, مصنعة لهذا الغرض, لتحديد خصائص رباطات القص المستخدمة.

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وقد وجد أنّ زيادة عدد رباطات القص يؤدي إلى زيادة سعة التحمل القصوى وتقليل كل من الإزاحة والإنزلاق في الأقواس المركبة وأنّ هذا السلوك يتحقق بشكل ملحوظ عند تقييد الحركة الأفقية للمساند (أقواس ذات إسناد مفصل- مفصل).

INTRODUCTION

In structural works, the required properties of the constructional materials are based on many factors such as availability, structural strength, stiffness, durability and workability. In effect, there is no natural material that possesses all these properties to the desired level. Therefore, different materials may be arranged in an optimum geometric configuration, with the aim that only the desirable property of each material will be utilized by virtue of its designated position. The structure is then known as a composite structure and the process is known as composite construction.

A large number of composite structures can be produced by the combination of different structural components, including rolled steel beams, built-up sections, timber beams, precast concrete beams, reinforced concrete slabs, steel plates and steel tubes. The most common composite structures in buildings and bridges are composite steel-concrete. Composite construction using steel and concrete has been used since the early 1920s. It gained widespread use in bridges in the 1950s and in buildings in the 1960s [1]. Composite action was first exploited in flexural members. Many types of composite steel-concrete beams are currently used in building and bridge construction. The most common one is that of composite T-section [2,3], shown in Figure(1) in which the reinforced concrete slab acts as the compression flange and the steel I-section acts as the web.

COMPOSITE ACTION

In Figure (1) the steel section is attached to the reinforced concrete slab by means of mechanical connectors. The functions of these connectors are to transfer tangential and normal interfacial forces between the two components, thus sustaining the composite action.

Two commonly used terms that describe composite behavior are partial shear connection and partial interaction, and these relate to the behavior of the connection between the steel and the concrete components [4, 5]. Partial shear connection concerns equilibrium of the forces within a composite member and it represents a strength criterion.

Partial interaction, on the other hand, concerns compatibility of deformations at the steel-concrete interface and it represents a stiffness criterion. It can be illustrated from a discussion of the lower and upper limits of the behavior of composite members, i.e., no interaction and complete interaction, Figure (2).

When the components of a composite member are not connected by any method of shear connections, then each component will freely slide over the other and will separately carry a part of the load. Assuming that the concrete behaves elastically in compression and tension, there will be two neutral axes: one at the centroid of the concrete section and the other at the centroid of the steel section. Without vertical separation between the slab and the beam, their curvatures at any given cross-section are equal. Therefore, the condition is equivalent to the pure bending of two members with equal curvatures along the span. The load carrying capacity of the composite member is not greater than the sum of the individual capacities of the two components. The situation is known as no interaction and is explained in Figure (2a).

If adequate connection is used so that the two components of the composite member are joined together by an infinitely stiff shear connection, the two components then behave as one and the displacement differences at the steel-concrete interface are everywhere zero. The situation is known as full or complete interaction and is explained in Figure (2b).

COMPOSITE ARCHES

An arch may be defined as a curved girder having convexity upwards, and supported at its ends. The shape of the arch may be circular, elliptical or parabolic and sometimes it is made up by circular arcs of several and different radii or/and centers. It may be subjected to in plane vertical, horizontal or even inclined loads.

In the past, the arches had been the backbone of the important buildings. But, in the present day, the arches are mostly being provided for the architectural beauty. However, because of relatively smaller values of bending moments and tensile stresses induced in the arch rib in comparison with the straight beam, it is preferred to utilize arched girders in structural purposes also. This characteristic enabled structural engineers to achieve large spans in buildings roofing and bridges decking using materials with efficient compressive strength, like concrete, or using suitable compression resisting systems, like braced and trussed metal structures to overcome the dominant compressive stresses generated in the arches.

In composite construction, both of material and structural system can be utilized when exploited in composite steel-concrete arches for large span roofing. As shown in Figure (3) steel arched girders may be arranged in a parallel way at regular intervals in the longitudinal direction of a tunnel or a building space carrying a cylindrical reinforced concrete slab which is attached to the steel arched girders by means of shear connectors to form together the roof surface.

Obviously such type of construction requires laboratory model testing to get a good insight picture of its actual structural behavior. Therefore, the present research will be directed towards studying the behavior of these arches with the inclusion of the effect of partial interaction and material nonlinearity by experimental test of composite arch models.

EXPERIMENTAL WORK

In experimental work, eight composite steel-concrete arches, designed to fail in bending, was fabricated as test specimens with four numbers of shear connectors and two types of support conditions.

Description of Test Specimens

The typical entire shape of any of the eight test specimens is part of a circle (circular arches) with cord length of 2000 mm as a span and height of 200 mm measured to the centerline of arched steel girder, as shown in Figure (4).

The typical specimen consisted of a reinforced concrete slab at the top and an arched steel I-girder at the bottom connected together by means of headed stud shear connectors welded to the top flange of steel girder. The concrete slab had a depth of 50 mm and a width of 300 mm and reinforced with one layer of rebars in two directions (four bars of diameter 4 mm in longitudinal tangential direction and reinforcing bars of diameter 4 mm at spacing of 110 mm center to center in transverse horizontal direction). The steel girder was formed by curving (bending) the European beam with parallel-faced flanges IPE100 about the strong (major) axis to the desired shape. The cross-section properties of IPE100 are given in Table (1). The headed stud

shear connector had a diameter of 10 mm and length of 38 mm. The typical cross-section of the specimen shown in Figure (5).

Two main variables were considered in this experimental investigation; namely, the support conditions and the number of the used headed stud shear connectors as listed in Table(2).

Two types of support system were used at the specimen ends. The hinge support system restrained all the translational movements while allowing the end rotation in the plane of the arch. The roller support system restrained vertical movement while allowing both of horizontal movement and end rotation in the plane of the arch. It must be noticed that the restraints provided by the hinge or roller supports of the specimen were applied to the arched steel girder exactly at its centerline, while the concrete slab was supported by the steel girder by means of the connectors. Furthermore, the entire arch shape of the specimen was defined by the centerline of the steel girder, as demonstrated in Figure (4).

Materials

Each test specimen was made of different materials and components i.e. steel, concrete, shear connectors and reinforcing bars, which were assembled together to constitute a composite steel-concrete arch. These materials have important effects on the structural response of the test specimens and must be individually evaluated.

Steel

Steel material was used in three situations, arched I-steel girder, reinforcing bars of concrete slab and headed stud shear connectors.

The European beam with parallel-faced flanges, IPE 100, was used to represent the arched steel girder. The cross-section dimensions and properties of this section are given in Table (1). To determine the mechanical properties of the steel material, a total number of seven tensile samples taken from the flanges and the webs of all the specimens were tested by using tensile testing machine. The average values of yield stress, ultimate strength and elongation are given in Table (3).

One layer of 4 mm diameter deformed bars was used in the longitudinal as well as the transverse direction of the reinforced concrete slab as shown in Figure (5). The mechanical properties of these bars are listed in the third row of Table (3) which represents the average of three control specimens of these bars tested in tension.

To resist the longitudinal shear at the interface between steel girder and concrete slab, and to prevent the vertical separation between them, headed stud shear connectors of diameter 10 mm and overall length 38 mm with a head of diameter 16 mm and height 7 mm were used in each test specimen. These studs were welded on the top flange of the steel girder.

A specimen of the original steel bolt was used to find-out the material properties of the stud in tension, Table (3). The behavior of the stud connector under direct shear was also evaluated by carrying out the so-called push-out tests as will be discussed later.

Concrete

The materials used in producing concrete are locally available materials, which include cement, natural gravel, natural silica sand and water. Ordinary Portland cement (Kuwaiti cement) was used throughout the investigation. The whole required quantity was brought to the laboratory and stored in a dry place.

Natural silica sand from Bahrel-Najaf area was used as fine aggregate with maximum size of 4.75 mm while natural gravel from Al-Niba'e region was used as coarse aggregate with maximum size of 12.0 mm. The natural gravel was washed and left in air, and then stored in a saturated dry surface condition before use. The grading

of fine and coarse aggregate was within the limits of Iraqi Specification No.45/1984 [6]. The ordinary potable water was used in making concrete and curing.

The same concrete mix was used through the whole investigation. The mix properties of the ingredients by weights were [1 cement: 2 sand: 4 gravel] and water cement (w/c) ratio was 57%, to give slump of about 50 mm.

Fabrication of Test Specimens

The fabrication of composite steel-concrete arch as a specimen for experimental test required several steps of steelworks, formworks and concreting.

Bending of Steel Girder

The arched steel girder was formed by bending (curving) the hot-rolled steel beam about its strong (major) axis to satisfy the desired arch shape. This process was carried out by using curving machine, shown in Figure (6). This equipment works by passing the hot-rolled steel beam through a set of rolls that gradually press and deform the straight steel beam into a circular arch with the required radius. The basic principle is illustrated in Figure (7) where the forces exerted by the rolls are applied on the top and bottom surfaces of the steel beam.

Figure (6) summarizes the bending process by photos. The beam was passed through the machine in a repeated manner to be bent into successively smaller radii of curvature. In each pass, the internal radius of the bent beam was checked by using wooden mold already fabricated for this purpose.

Heat Treatment

During the bending (curving) of the steel beam, a certain amount of plastic deformation must take place in the cross-section in order for the bending process to work. Bending causes large (plastic) axial strains in the extreme fibers of the cross-section. The welding process, on the other hand, causes high temperatures on parts of the steel girder. Bending and welding result in residual stresses within the body of the steel girder.

To relieve (or reduce) these stresses, heat treatment was carried out on the resulting steel girders. The girders were tied up together and braced by steel rods to keep them in one form. This assembly was entered into furnace, heated up to 600-650 C° with a heating rate of 150 C°/hr, fixed at this temperature for about 15 minutes and finally left inside the furnace to be cooled slowly [7].

Concrete Works

A reinforced concrete cylindrical shell was made on the top of the arched steel girder as a concrete slab in manufacturing of the composite arches.

Steel plates and angles were used in manufacturing formworks for this purpose. During casting of each composite arch, three 100×100×100 mm cubes and three 100×200 mm cylinders were made. Cube compressive strength and cylinder tensile strength were obtained by standard tests. The results of each composite arch are averaged and given in Table (4).

Instrumentation and Test Setup

Tests were carried out at the structure laboratory of college of Engineering, University of Kufa, using universal testing machine with capacity of 2000 kN, Figure (8).

Eight dial gauges of accuracy 0.01mm were used to measure vertical deflection, horizontal displacement or slip at different locations. The locations and directions of these gauges are shown in Figure (9) while their details are given in Table (5).

The eight specimens were tested under concentrated load. The load was slowly applied in successive increments up to failure. During testing, the surface of concrete

was carefully inspected for developing cracks. Test was terminated at the onset of one of the following;

- Substantial drop in the value of the total applied load.
- Excessive deformations and cracks widening under the same load level.
- Crushing of concrete and/or shearing of studs.

Push-Out Test

The shear behavior of stud in a composite steel-concrete member can only be determined by experimental tests. To investigate this behavior under direct shear, push-out tests were carried out on three specimens (P1, P2 and P3) fabricated within the frame of the present investigation using the same materials and components and the same cross-section dimensions, as shown in Fig-10. The flanges of a short length of IPE100 were connected to two 50 mm thick concrete slabs by four welded $\phi 10$ mm studs and a steel plate of 6 mm thickness was welded to the upper end of the steel beam.

Relative slip between the steel beam and the two slabs (i.e. vertical displacement of steel) was measured at each increment of loading by the use of two dial gauges affixed on the two sides of steel beam web. A test was terminated when one of the stud connectors at any location was fractured as shown in Figure (11).

In Figure (12) the average slip is plotted against the load per one connector for each specimen.

RESULTS AND DISCUSSION

The eight specimens are categorized into two groups according to their support conditions, the Hinge-Hinge supported arches and the Hinge-Roller supported arches, with different numbers of stud shear connectors used for each group, to investigate the effects of support conditions and degree of shear connection on the structural behavior of composite arches.

Ultimate Loads and Cracks Pattern

The load on specimens is applied monotonically in increments. These increments are reduced in magnitude as the load reaches the ultimate load. All these specimens finally failed by crushing of concrete slab at the extreme compression fibers (top surface of concrete slab) in the region of maximum positive (+ve) bending moment (midpoint of the arch, under load diffuser) after excessive increase in deflection and cracks width under constant load level. The maximum load recorded by the testing machine is considered as the ultimate load and is given in Table(6).

The general trend in ultimate load values, P_u , for each group of specimens, is to increase by increasing the number of shear connectors (degree of shear connection). But, this trend is influenced, in the case of Hinge-Roller supported arches, by the relatively high concrete strength of HR11 and the relatively low concrete strength of HR15 which resulted in similar values of ultimate load. The similar obtained values of ultimate load for HR21 and HR25 may be interpreted as the use of a number of shear connectors more than 21 has an insignificant effect on the predicted values of P_u for Hinge-Roller supported arches with this shape and cross-section properties.

However, the abovementioned general trend can obviously be noticed in the case of Hinge-Hinge supported arches.

By comparing the results of the two groups, substantial increase in ultimate load is obtained when the horizontal movements of supports are constrained (Hinge-Hinge supported arches) for specimens with the same number of shear connectors. The percentage increase ranges between 93% for specimens with 11 connectors to 138% for specimens with 25 connectors.

During testing, the surface of concrete is carefully inspected for developing cracks. The first cracks in all specimens appeared at the extreme tension fibers (bottom surface of concrete slab) in the region of maximum positive bending moment. Then, longitudinal cracks formed in concrete slab due to the lateral tensile forces induced in the slab caused by the dowel action of individual shear connectors.

For the case of Hinge-Hinge supported arches, additional transverse cracks formed before failure at the extreme tension fibers (top surface of concrete slab) in the region of maximum negative (-ve) bending moment (approximately at the quarter arch length).

Photos shown in Figure (13 and 14) reveal the state of HR21 and HH21 after test, respectively.

Vertical Deflection and Horizontal Displacement

Each of concrete slab and steel girder has its own vertical deflection value due to uplift (separation between concrete slab and steel beam). However, uplift values are very small compared with deflection values. Therefore, the deflection values of concrete slab and steel girder are assumed to be equal in the discussion of deflection results presented in this section. It must be noticed that the deflection values in the experimental tests are for arched steel girder. The horizontal displacements of composite arches are only measured for Hinge-Roller supported arches where the horizontal movements of their supports are permitted.

The load versus mid-span deflection curves for the Hinge-Roller and Hinge-Hinge supported arches are respectively shown in Figure (15, 16, 17 and 18) show the deflection distribution along the arch span under service and ultimate load levels for the Hinge-Roller and Hinge-Hinge supported arches, respectively. In this study, any common load level (in one group of specimens) smaller than 60% of ultimate load is assumed as service load level.

For the case of Hinge-Roller supported arches, the deflection, at the same load level, decreases when the number of shear connectors increases from 11 to 25. This trend is true for the case of Hinge-Hinge supported arches. However, it can be noticed that the two load-midspan deflection curves corresponding to specimens HH15 and HH21 are close to each other, and the abovementioned trend of these two curves is violated within an intermediate range (nonlinear range) of loading history. This may be attributed to the relatively high concrete strength of HH15 and relatively low one of HH21. Also, it must be recalled that the imperfections in specimens fabrication and test setup considerably affects the accuracy of the test results.

On the other hand, a Hinge-Roller supported arch is deflected greater than the corresponding Hinge-Hinge supported arch having the same number of shear connectors. At the same load level, about (53-64) % decrease in deflection is obtained when the horizontal movements of supports are constrained.

Figure (19) shows the load versus horizontal displacement for Hinge-Roller supported arches. By considering the comparison depicted in this Figure, it can be seen that the horizontal displacements of roller supports are also decreased by increasing the number of shear connectors.

Slip between Steel and Concrete

The variation of the experimentally measured values of the end slip with load are presented in Figure (20 and 21) for Hinge-Roller and Hinge-Hinge supported arches, respectively. The effect of the degree of partial shear connection on the end slip embodies through that when the number of shear connectors increases from 11 to 25, the measured end slip considerably decreases.

Figure (22 and 23) show the slip distributions along the arch circumferential length under service and ultimate load levels for the Hinge-Roller and Hinge-Hinge supported arches, respectively.

For each specimen, the distribution of longitudinal slip values along the arch circumferential length is estimated at a specified load level by passing a spline curve through the points of slips experimentally measured at that load level where s represents the circumferential distance on the interface of the composite arch measured from the left support, and L_i represents the circumferential length of the interface layer.

CONCLUSIONS

Based on the results obtained from this investigation, the followings can be concluded

- The general trend in ultimate load values, P_u , for each group of specimens, is to increase by increasing the number of shear connectors (degree of shear connection).
- A substantial increase in ultimate load is obtained when the horizontal movements of supports are constrained for specimens with the same number of shear connectors.
- At the same load level, the vertical deflection, horizontal displacement and slip increase when the degree of shear connection decreases. This is true for both types supporting systems.
- The deflection and slip values for Hinge-Hinge supported specimens are smaller than those for Hinge-Roller supported specimens at the same load level.

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Table (1) Cross-section properties of the used steel section.

Section name	IPE 100
Weight per length	8.10 kg/m
Cross-sectional area, A	1 030 mm ²
Section depth	100.0 mm
Flange width, B_f	55.0 mm
Flange thickness, t_f	5.7 mm
Web thickness, t_w	4.1 mm
Moment of inertia, I	1.710 × 10 ⁶ mm ⁴

Table(2) Details of test specimens.

Specimen Name	Support Conditions	No. of shear connectors
HH11	Hinge-Hinge	11
HH15	Hinge-Hinge	15
HH21	Hinge-Hinge	21
HH25	Hinge-Hinge	25
HR11	Hinge-Roller	11
HR15	Hinge-Roller	15
HR21	Hinge-Roller	21
HR25	Hinge-Roller	25

Table(3) Mechanical properties of the steel used in the test specimens.

Item	Yield stress N/mm^2	Tensile strength N/mm^2	Elongation %
Flanges of steel girder IPE 100	306	451	59
Web of steel girder IPE 100	286	398	47
Reinforcing bars ϕ 4 mm	433	484	36
Stud connector ϕ 10 mm	244	274	27

Table (4) Concrete strength of test specimens.

Specimen Name	Cube Compressive Strength (N/mm^2)	Cylinder Tensile Strength (N/mm^2)
HR 11	32.7	2.03
HR 15	29.1	1.85
HR 21	31.1	2.01
HR 25	30.8	1.97
HH 11	31.8	2.53
HH 15	33.5	2.21
HH 21	30.4	2.06
HH 25	32.0	2.15

Table (5) Details of dial gauges.

Gauge No.	Type of specimen	Type and location of displacement to be measured
1	Hinge-Hingeand Hinge-Roller arches	Vertical deflection of arched steel girder at midspan.
2 or 3	Hinge-Hingeand Hinge-Roller arches	Vertical deflection of arched steel girder at 1/4 span.
4 or 5	Hinge-Hingeand Hinge-Roller arches	Interface slip at specimen end.
6 or 7	Hinge-Hingeand Hinge-Roller arches	Interface slip at 1/4 interface length (Li).
8	Hinge-Hingearches only	Interface slip at 1/2 interface length (Li).
8	Hinge-Rollerarches only	Algebraic sum of horizontal displacements of roller supports.

Table (6) Experimental values of ultimate loads.

Specimen Name	Ultimate Load $P_u(kN)$
HR11	41
HR15	41
HR21	45
HR25	45
HH11	79
HH15	97
HH21	101
HH25	107

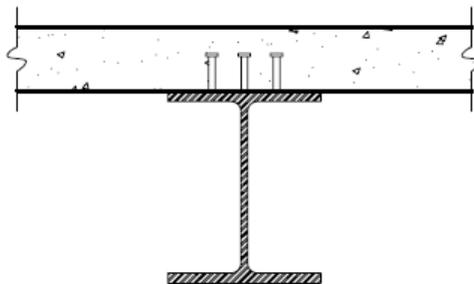


Figure (1) Composite T-section.

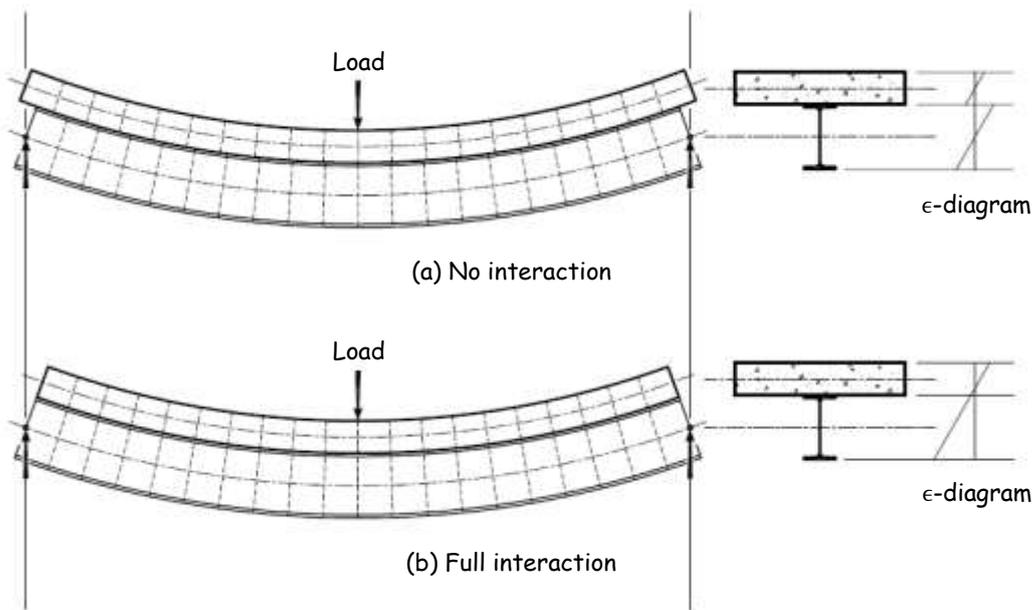


Figure (2) Behavior of composite member.

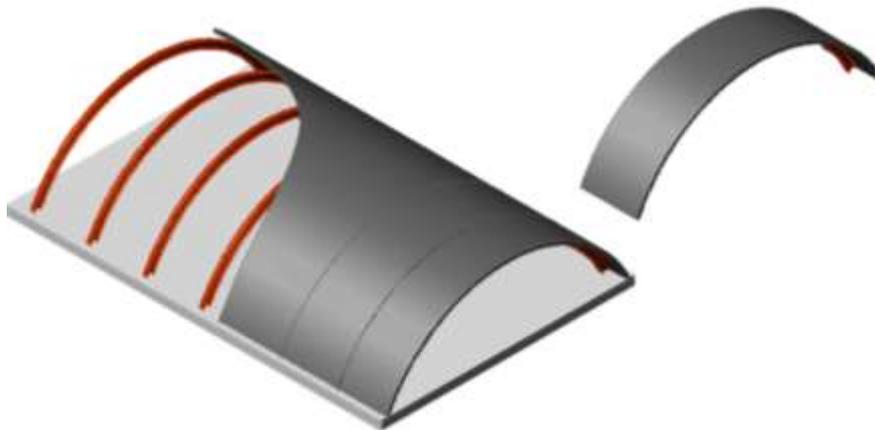


Figure (3) Composite steel-concrete arches.

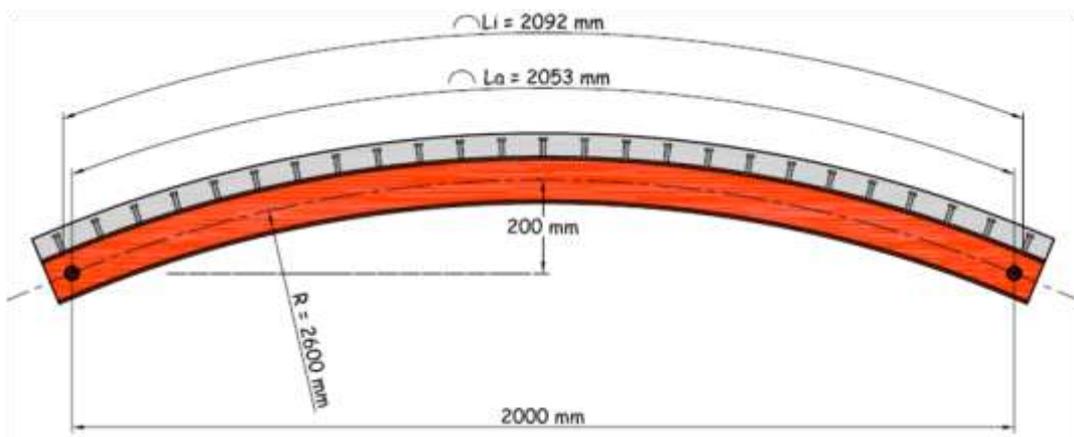
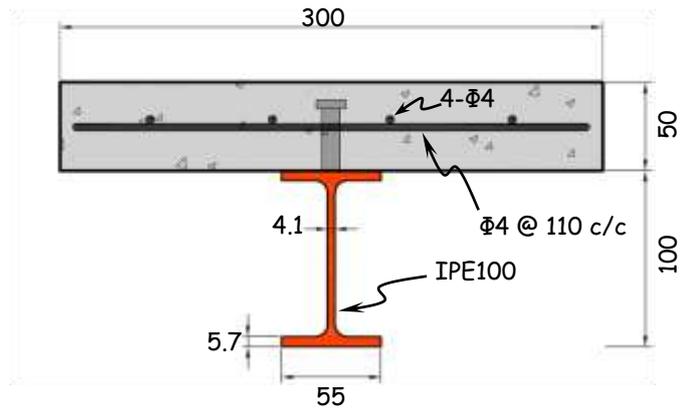


Figure (4) typical shape of a composite steel-concrete arch specimen.



All dimensions are in

Figure (5) Typical cross-section of composite arch test specimens.



Figure (6) Photos of curving (bending) process.

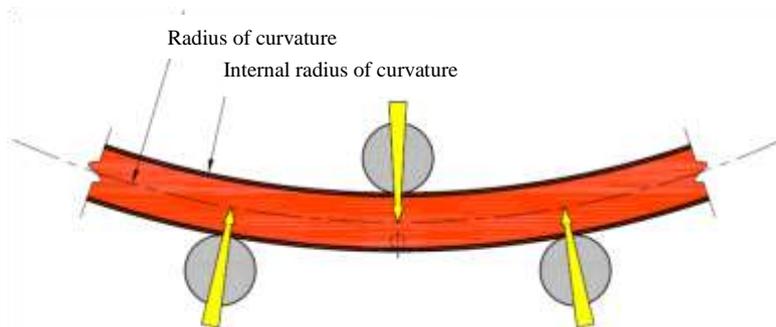


Figure (7) Principle of curving process.



Figure (8) Photo of universal testing machine.

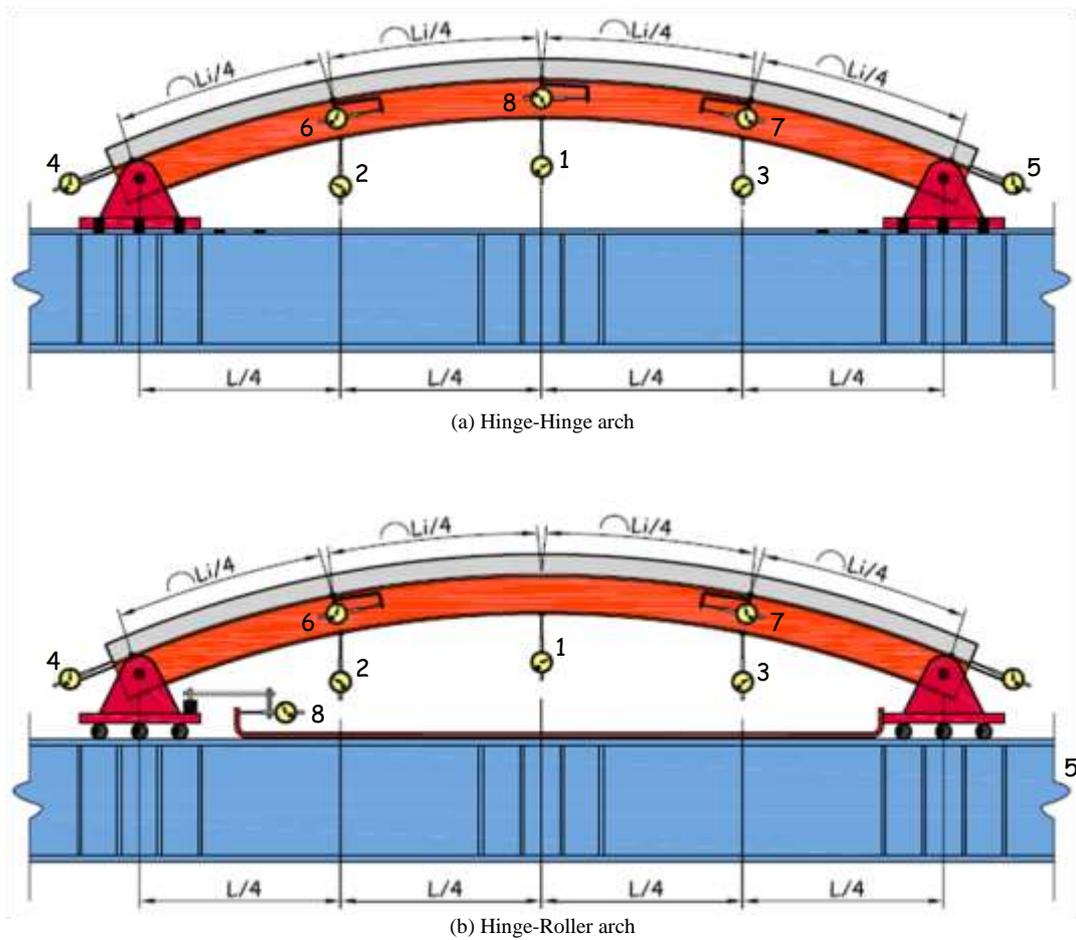


Figure (9) Distribution of dial gauges.

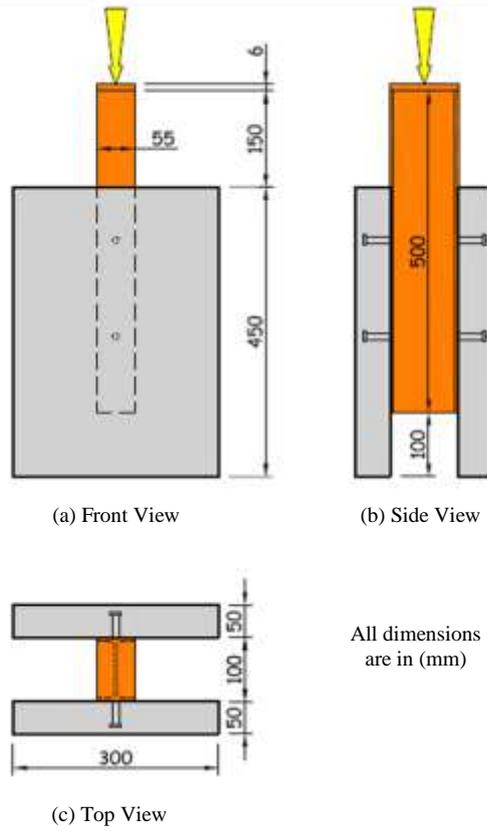


Figure (10) Details of push-out test.





Figure (11) Photos of push-out test specimens.

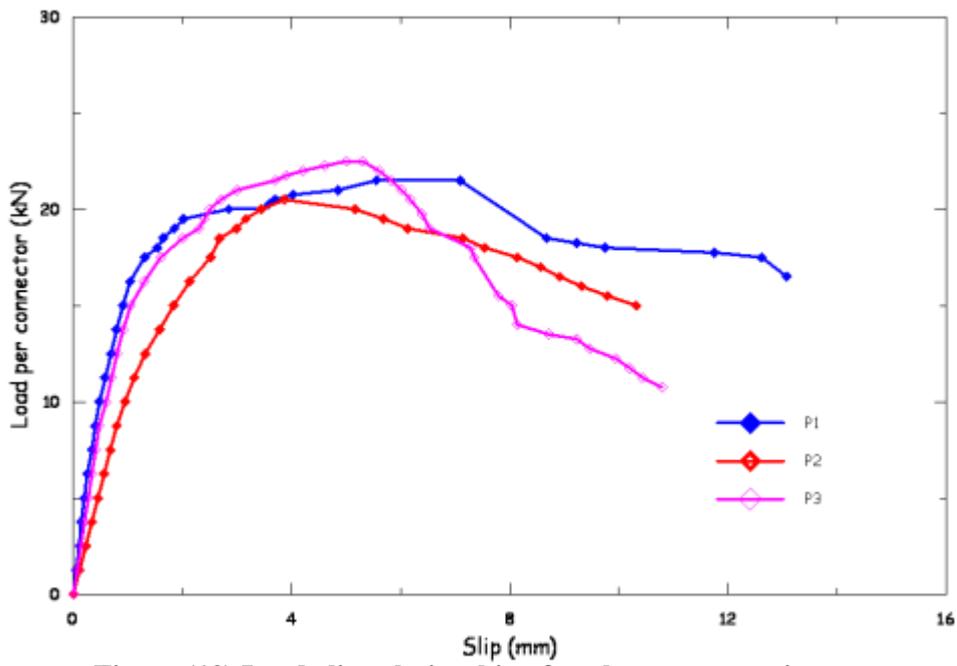


Figure (12) Load-slip relationship of push-out test specimens.



(a) Tension cracks & concrete crushing at region of max. +ve moment, front



(b) Tension cracks at region of max. +ve moment, rear view.



(c) Concrete crushing at region of max. +ve moment, top surface.



(d) Longitudinal cracks at right side & concrete crushing at max. +ve



(e) Longitudinal cracks at left side, top surface.



(f) Longitudinal cracks at right end.

Figure (13) Photos of tested specimen HR21.



(a) Tension cracks & concrete crushing at region of max. +ve moment, rear



(b) Tension cracks at region of max. +ve moment, front view.



(c) Transverse crack at max. -ve moment & longitudinal cracks at right side.



(d) Longitudinal cracks at left side, top surface.



(e) Longitudinal cracks at left end.



(f) Longitudinal cracks at left side, bottom surface.

Figure (14) Photos of tested specimen HH21.

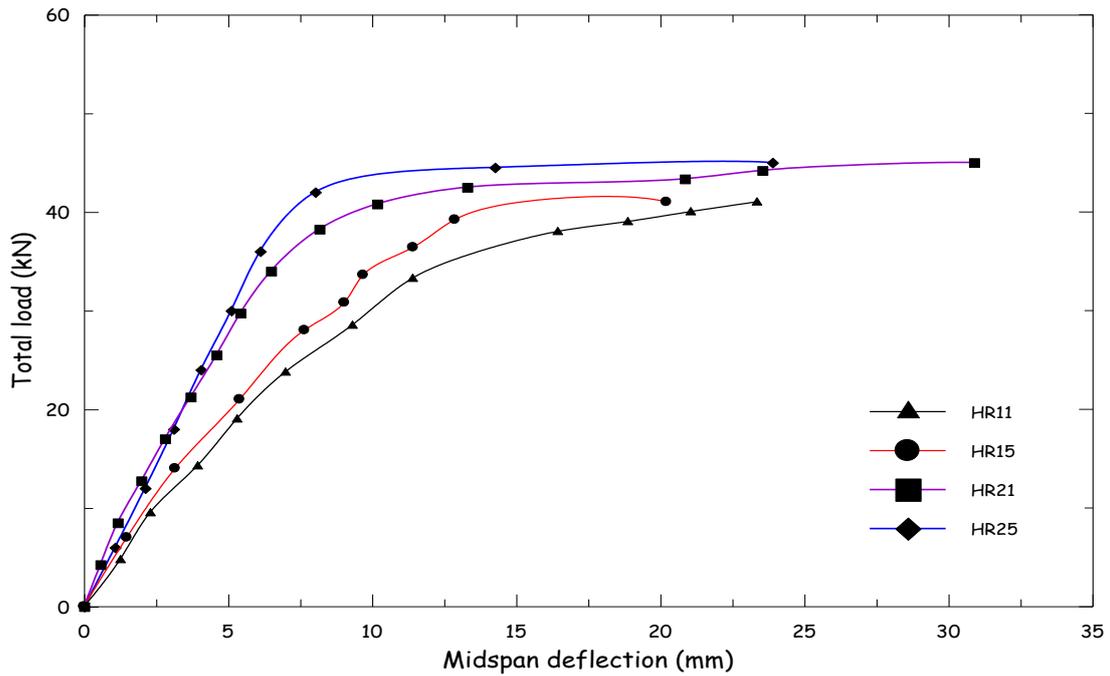


Figure (15) Load-midspan deflection curve of Hinge-Roller supported arches with different number of connectors.

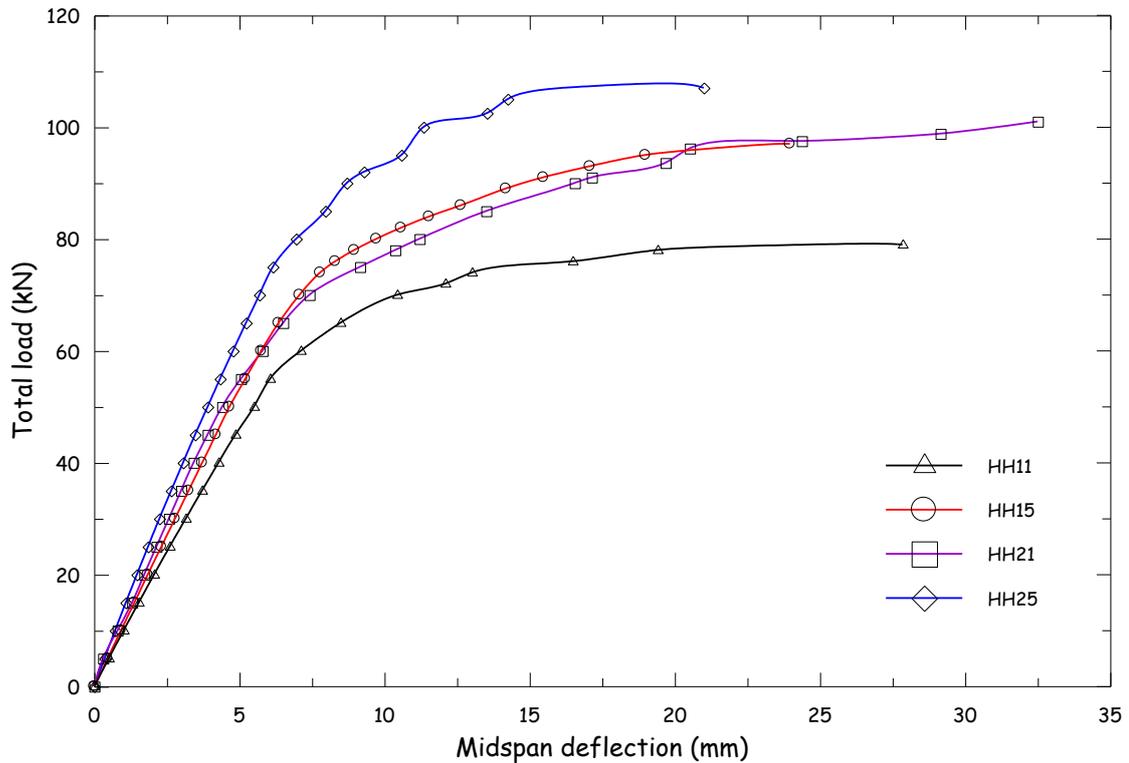


Figure (16) Load-midspan deflection curve of Hinge-Hinge supported arches with different number of connectors.

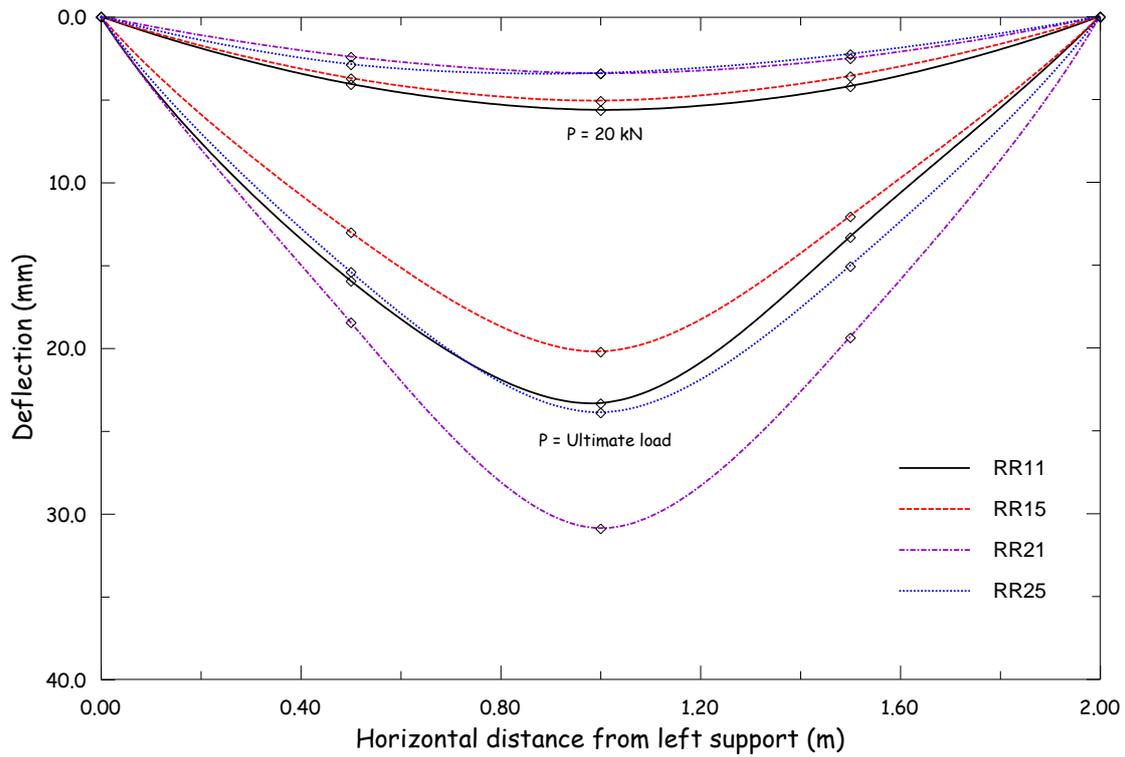


Figure (17) Deflection distribution along arch span at service and ultimate load levels for Hinge-Roller supported arches.

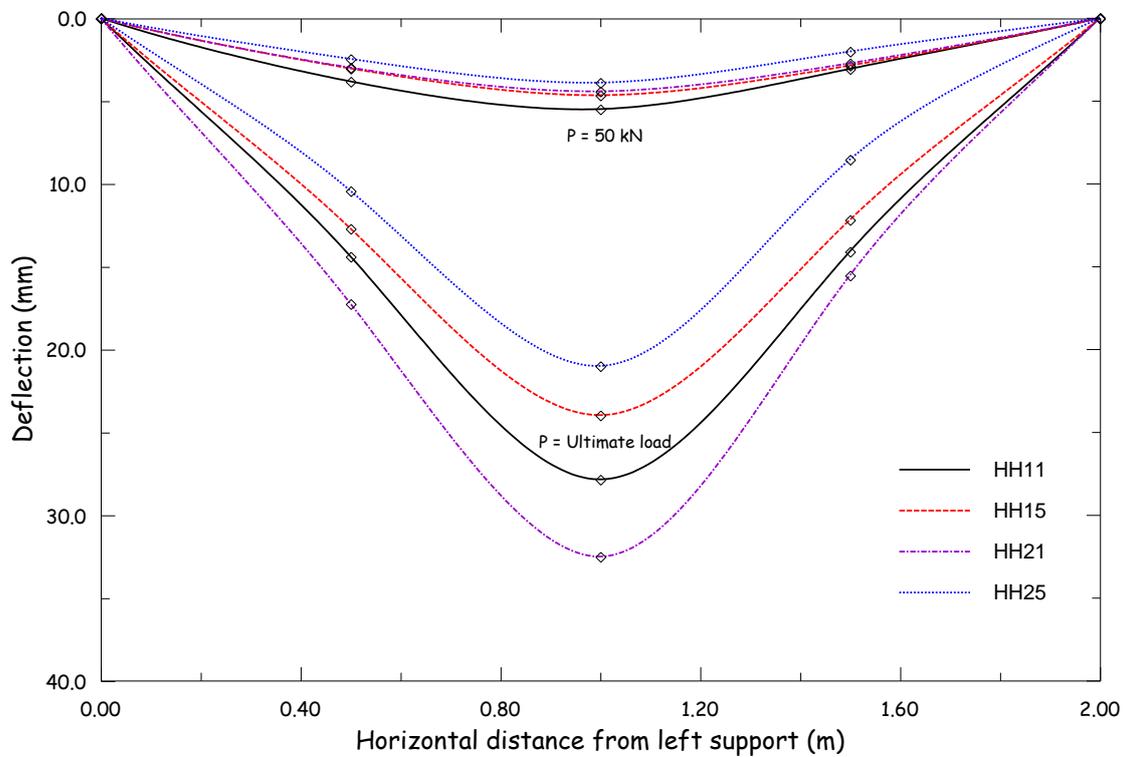


Figure (18) Deflection distribution along arch span at service and ultimate load levels for Hinge-Hinge supported arches.

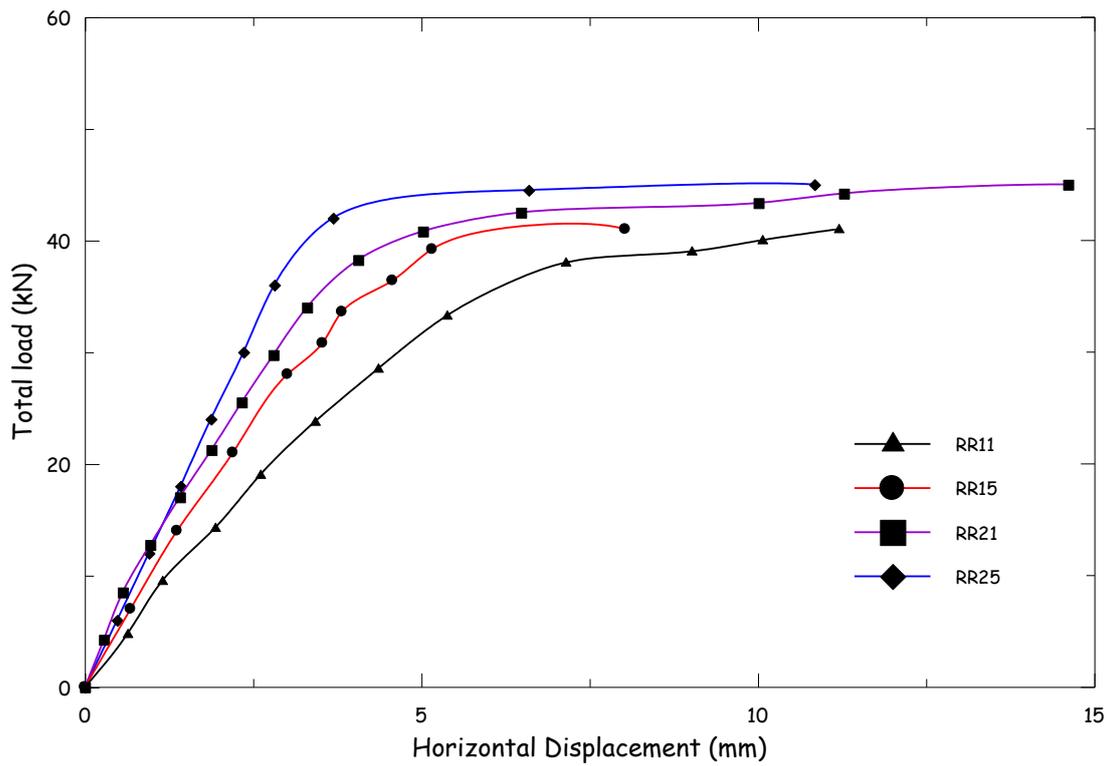


Figure (19) Load-horizontal displacement curve of Hinge-Roller supported arches with different number of connectors.

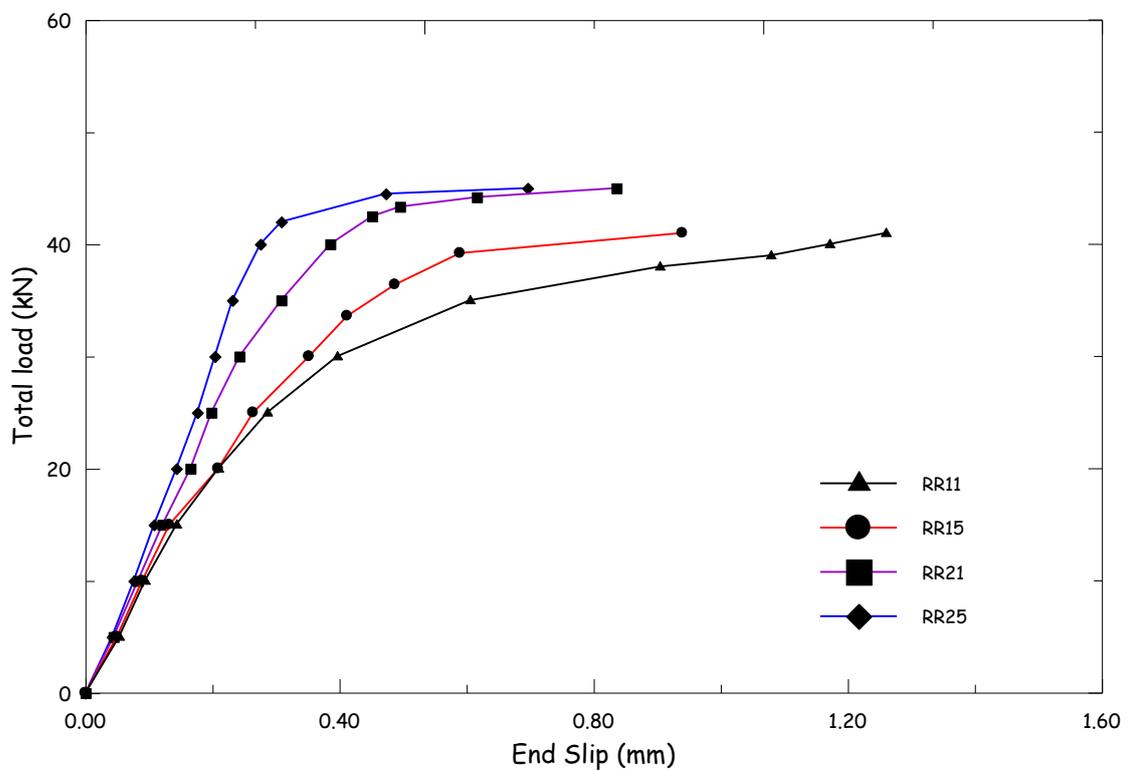


Figure (20) Load-end slip curves of Hinge-Roller supported arches with different number of connectors.

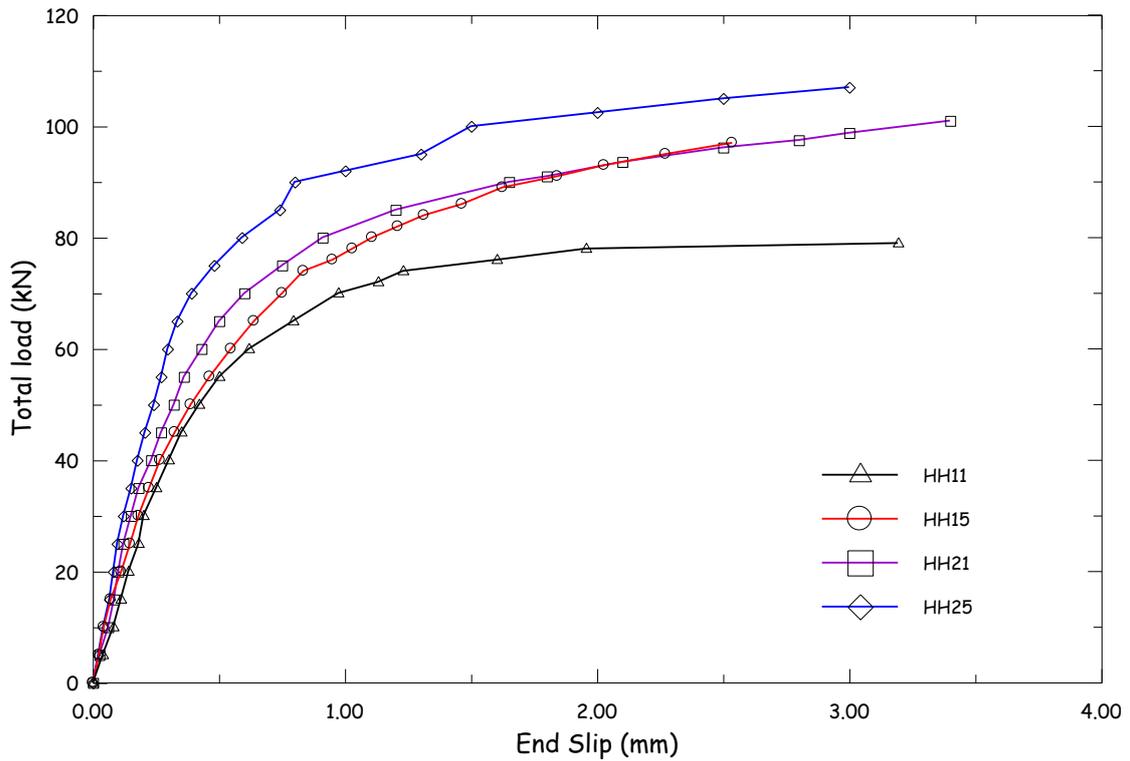


Figure (21) Load-end slip curves of Hinge-Hinge supported arches with different number of connector.

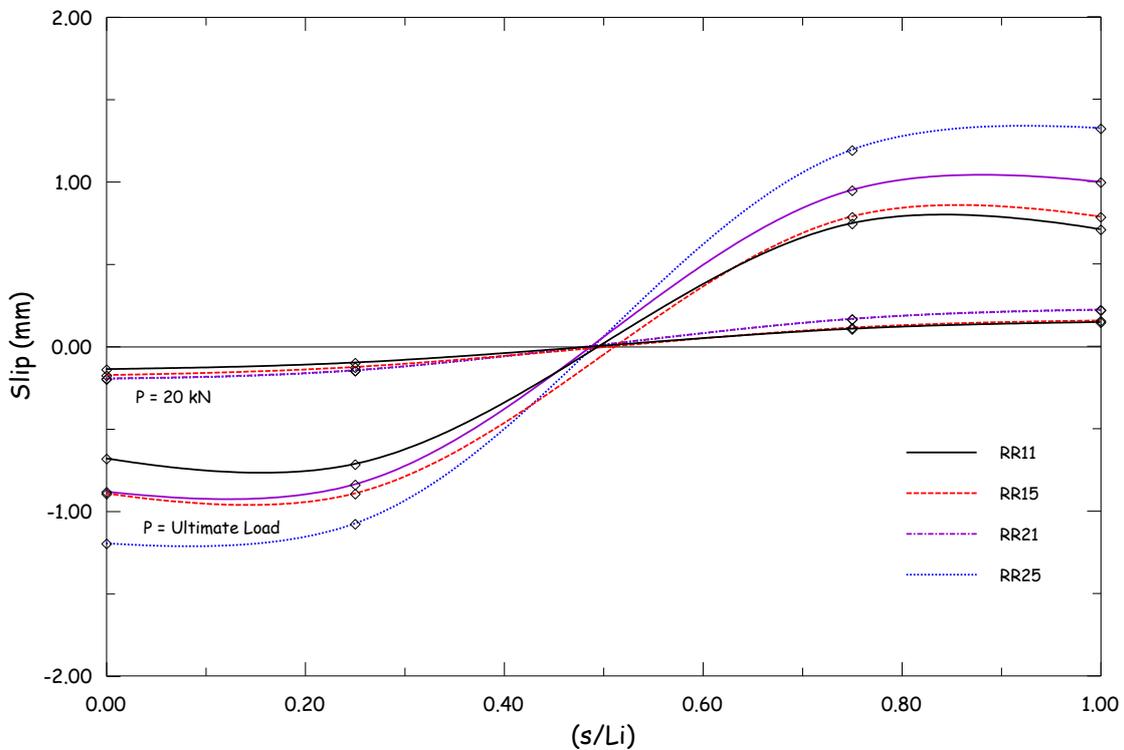


Figure (22) Slip distribution along arch circumferential interface length at service and ultimate load levels for Hinge-Roller.

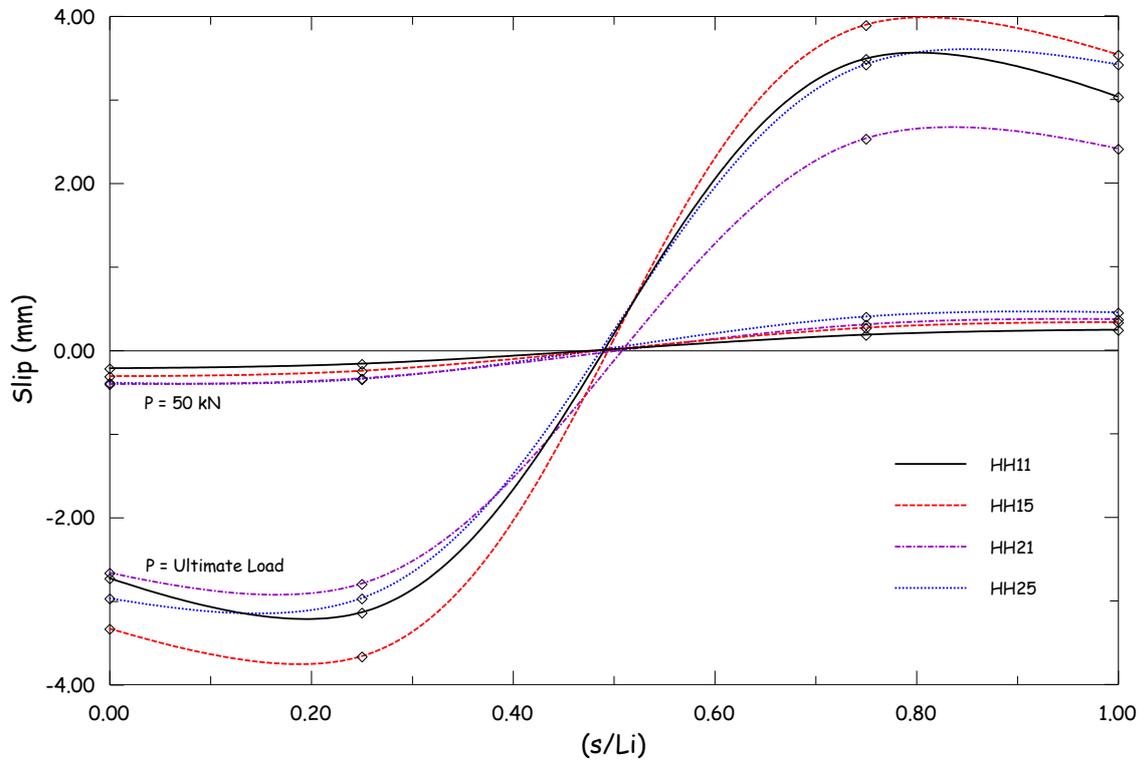


Figure (23) Slip distribution along arch circumferential interface length at service and ultimate load levels for Hinge-Hinge.