Finite Element Analysis of Concrete-to-Concrete Friction

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Abstract: ***This article is focused on the numerical analysis of the shear resistance at an interface between two concretes cast at different times, which performed by means of a nonlinear finite element program. A linkage element and an interface element had been used, in this study, to model the dowel action and the concrete shear transfer at the interface, respectively. The finite element idealization had been verified by the analysis of several specimens tested by others. The comparison shows a good concordance with the experimental results within acceptable ranges.***

Keywords: concrete, finite element, friction, interface, nonlinear analysis

1. Introduction

The main goal of this research was to verify the finite element procedure presented by Al-Sherrawi (2001) [1] to represent the interface between two concretes cast at different times under shear. A two-dimensional plane stress finite element type had been used to model the concrete specimens. Mahmoud and Al-Sherrawi [2] used this procedure in the analysis of composite concrete beams. Al-Sherrawi [3] extended it to three dimensional modeling.

When shear acts along a crack, one crack face slips relative to the other. If the crack faces are rough and irregular, this slip is accompanied by separation of the crack faces. At nominal strength, the separation is sufficient to stress, in tension, the reinforcement crossing the crack to its specified yield strength. The reinforcement in tension provides a clamping force across the crack faces. The applied shear is then resisted by friction between the crack faces, by resistance to the shearing off of protrusions on the crack faces, and by dowel action of the reinforcement crossing the crack [4].

Several experimental investigations of concrete-to-concrete friction specimens had been done in literature. Birkeland and Birkeland [5] and Mast [6] developed a philosophy of connection design in which cracks are assumed to have occurred disadvantageous locations within the region of the connection. Chatterjee [7] and Vangsirirungruang [8] studied the influence of direct stresses acting parallel and transverse to the shear plane.

It was found by Mattock and Hawkins [9] that for given value of f_y, the specimens with 464 MPa (66 ksi) steel had slightly higher shear strength than the specimens reinforced with the 350 MPa (50 ksi) steel. This appears to indicate that at ultimate strength the higher strength steel stirrups developed a stress greater than their yield point, i.e., strain hardening had occurred. This is quite possible, as the yield plateau of the higher strength reinforcement is considerably shorter than that of the intermediate grade reinforcement. It therefore appears conservative to assume that the relationship between ρf_y and v_u is the same for higher strength reinforcement as for intermediate grade reinforcement, provided the yield strength does not exceed 464 MPa.

Mattock et al. [10] studied the effect of moment and normal force in the shear plane on single direction shear-transfer strength. Tests were reported of corbel type push-off specimens and of push-off specimens with tension acting across the shear plane. A typical specimen is shown in Figure 1.

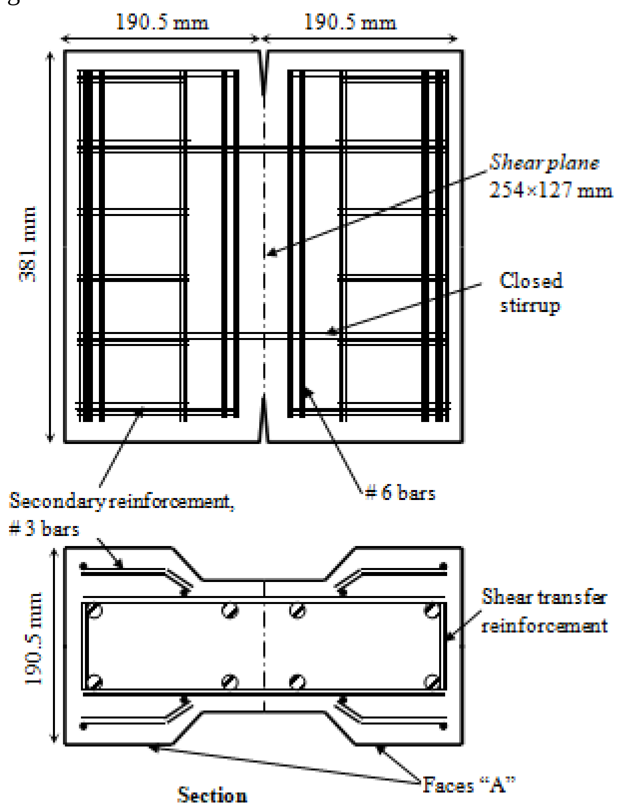

Figure 1: Shear transfer specimen CB2M [10]

Subsequently Mattock et al., [11] showed that the shear transfer strength of lightweight concrete under monotonic load is inferior to that of normal weight concrete of the same compressive strength. They proposed that the shear transfer strength of all-lightweight concrete and of sand-lightweight concrete be taken, respectively, as 0.75 and 0.85 times the shear transfer strength of normal weight concrete of the same compressive strength and having the same reinforcement.

In all cases, the shear transfer reinforcement crosses the shear plane at right angles and is securely anchored so that it can develop its yield strength in tension. Additional reinforcement was provided away from the shear plane, to prevent failures other than along the shear plane. For convenience, the ultimate shear strengths were expressed as average-shearing stresses (v_u), obtained by dividing the ultimate shear force (V_u) by the area of the shear plane.

To study the influence of cyclic shear transfer, Mattock [12] made tests on a crack in monolithic concrete or an interface between concretes cast at different times.

The most important aspect of the joining of two concretes is the strength of the bond that can be achieved. This bond is crucial, as it determines what forces can be transferred across the junction between the two concretes [13].

2. Shear Transfer across Crack

The assumption that cracked concrete cannot transfer shear forces across the crack interface is not realistic. Experiments show that a considerable amount of shear stress can be transferred across the rough surfaces of cracked concrete. In plain concrete, the main shear transfer mechanism is aggregate interlock and the main variables involved are the aggregate size and grading. In reinforced concrete, dowel action will play a significant role; the main variables are the reinforcement ratio, the size of the bars and the angle between crack and bars [14].

The experimental data presented by Poli et al. [15] will be utilized to proposed the following simplified mathematical model for the secant stiffness of dowel action against core (k_d):

$$k_d = \frac{20+5(d_b-14)}{1.5}|\Delta| \qquad |\Delta| \le 1.5 \text{ mm}$$

$$k_d = \frac{20+5(d_b-14)}{|\Delta|} \qquad |\Delta| \ge 1.5 \text{ mm} \qquad (1)$$

where d_b is diameter of the bar; and Δ is dowel displacement. These equations are shown in Figure 2.

Fronteddu et al. [16] utilized their experimental results from displacement controlled shear tests on concrete lift joint specimens with different surface preparations, to propose an empirical interface constitutive model based on the concept of basic friction coefficient (μ_b) and roughness friction coefficient (μ_i):

$$\mu = \frac{\lambda_d \mu_b + \chi_i \mu_i}{1-\lambda_d \chi_i \mu_b \mu_i} \qquad (2)$$

where $\mu_b = 0.950\text{-}0.220\, \sigma_n$ for $\sigma_n \le 0.5\text{MPa}$

$\mu_b = 0.865\text{-}0.050\, \sigma_n$ for $0.5 \le \sigma_n \le 2.0\text{MPa}$

μ_i is defined by the equations in Table 1. Two correction factors were introduced: (1) λ_d, the dynamic reduction factor equal to 1.00 for static loading and 0.85 for dynamic loading; and (2) χ_i, the interface roughness factor equal to 1.00 for cracked homogeneous concrete, 0.80 for water-blasted joints, 0.15 for untreated joints, and 0.00 for flat independent concrete surfaces.

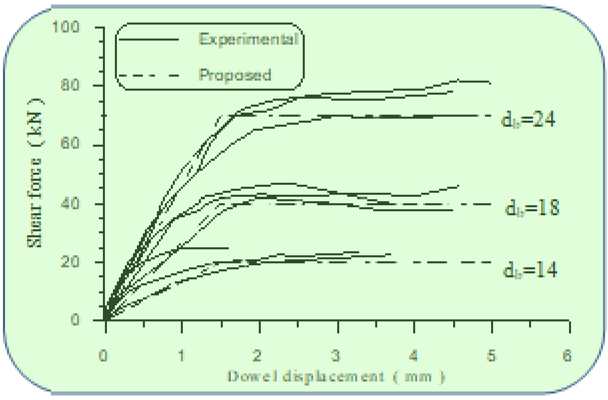

Figure 2: Proposed dowel stiffness

Table 1: Concrete interface model roughness coefficient [16]

Interface type	σ_n *(MPa)*	*Peak* μ_{ip}
homogeneous	$\sigma_n \le 0.4$ $0.4 \le \sigma_n \le 1.5$ $1.5 \le \sigma_n \le 2$	0.90-1.367 σ_n 0.40-0.1167 σ_n 0.30-0.050 σ_n
water-blast	$\sigma_n \le 0.275$ $0.275 \le \sigma_n \le 1.2$ $1.2 \le \sigma_n \le 2$	0.875-1.75 σ_n 0.44-0.185 σ_n 0.25-0.0375 σ_n
untreated	$\sigma_n \le 1.0$ $1.0 \le \sigma_n \le 2.0$	0.15-0.15 σ_n 0.05-0.005 σ_n

Based on the experimental results presented by Fronteddu et al. [16], a bilinear relationship between shearing stress and slip is adopted, Figure 3.

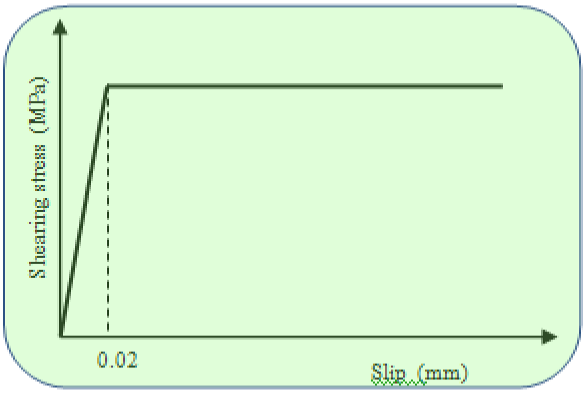

Figure 3: Adopted shearing stress-slip relationship

3. Finite Element Idealization

The finite element idealization of reinforced concrete specimens should be able to represent concrete cracking, the interaction between concrete and reinforcement, and the capability of concrete to transfer shear after cracking by aggregate interlock.

To create such an idealization, the following element types had been used:

- Plane stress elements to represent concrete.
- Line elements to represent reinforcement.
- Linkage elements to represent the bond between concrete and reinforcement and the dowel action.
- Interface elements to represent shear-transfer.

3.1 Linkage Element

In order to represent the bond slip phenomenon, linkage elements are used to link the concrete and the reinforcement nodes that occupy the same location. Also, it is used to represent the aggregate interlock and the dowel action in discrete crack representation; and will be used, in this research, to connect between concrete and concrete elements. A linkage element may be thought as being composed of two orthogonal springs each with a given stiffness depending on the phenomenon they describe. The linkage element has no physical dimensions at all, and only its mechanical properties are of importance. Figure 4 shows such an element oriented at an arbitrary angle (θ) relative to the global coordinate system.

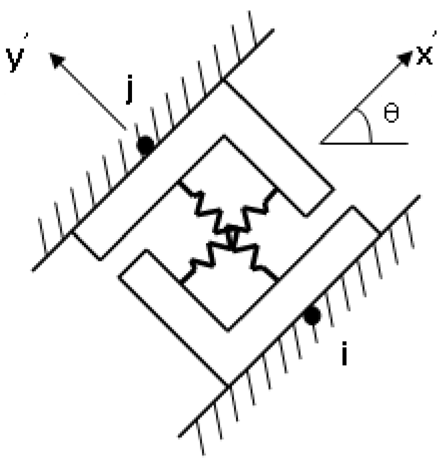

Figure 4: Linkage element

To incorporate the linkage element into the finite element computer program, it is necessary to develop the stiffness matrix of the linkage element. Let the springs in the local horizontal and vertical directions have stiffness K_h and K_v, respectively. The stress-strain relationship is given by Ngo and Scordelis [17]:

$$\begin{Bmatrix} \sigma_h \\ \sigma_v \end{Bmatrix} = \begin{bmatrix} K_h & 0 \\ 0 & K_v \end{bmatrix} \begin{Bmatrix} \varepsilon_h \\ \varepsilon_v \end{Bmatrix} \tag{3}$$

or

$$\{\sigma\} = [C]\{\varepsilon\}$$

where σ_h and σ_v are relative forces; ε_h and ε_v are relative displacements between points (i) and (j) in the local horizontal and vertical directions and are positive when they are tension. The strains and the global displacements are related by the displacement transformation matrix [A]:

$$\{\varepsilon\} = [A]\{u\} \tag{4}$$

or

$$\begin{Bmatrix} \varepsilon_h \\ \varepsilon_v \end{Bmatrix} = \begin{bmatrix} -c & -s & c & s \\ s & -c & -s & c \end{bmatrix} \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \end{Bmatrix} \tag{5}$$

where c = cosθ and s = sinθ

By noting that the force transformation matrix [B] is equal to the transpose of the displacement transformation matrix [A], the stiffness of the linkage element can be obtained from:

$$[K] = [A]^T [C] [A] \tag{6}$$

$$= \begin{bmatrix} k_{11} & k_{12} & -k_{11} & -k_{12} \\ & k_{22} & -k_{12} & -k_{22} \\ & & k_{11} & k_{12} \\ & & & k_{22} \end{bmatrix} \tag{7}$$

where $k_{11} = K_h \cos^2\theta + K_v \sin^2\theta$
$k_{12} = (K_h - K_v) \cos\theta \sin\theta$
$k_{22} = K_h \sin^2\theta + K_v \cos^2\theta$

3.2 Interface Element

At the interface, there can be separation, closing of the gap, and slipping between the two concretes. A four-noded interface element as shown in Figure 5 had been used to model this behavior between concrete elements of the two parts [1]. Two in-plane translational degrees of freedom per node have been considered. The displacement vector is:

$$\{\delta\} = [u \quad v]^T \tag{8}$$

The strains are the relative displacements at the top and bottom of the element. The strain vector is defined as:

$$\{\varepsilon\} = [\Delta u \quad \Delta v]^T \tag{9}$$

The relevant stress vector is:

$$\{\sigma\} = [\sigma_u \quad \sigma_v]^T \tag{10}$$

The material modulus matrix is defined as:

$$[D] = \begin{bmatrix} k_s & 0 \\ 0 & k_n \end{bmatrix} \tag{11}$$

Where k_s and k_n are the shear and the normal stiffness coefficients, respectively. The strain matrix is defined as:

$$[B] = [-[I]N_1 \quad -[I]N_2 \quad [I]N_1 \quad [I]N_2] \tag{12}$$

Where [I] is identity matrix of order (2×2), and N_i are the shape functions. The stiffness matrix is calculated as:

$$[K_L] = \int [B]^T \cdot [D] \cdot [B] \cdot dx \tag{13}$$

Two Gauss points had been used to calculate the stiffness matrix. The stiffness matrix in the global coordinate system had been calculated as:

$$[K_G] = [T]^T \cdot [K_L] \cdot [T] \qquad (14)$$

Where [T] is the transformation matrix.

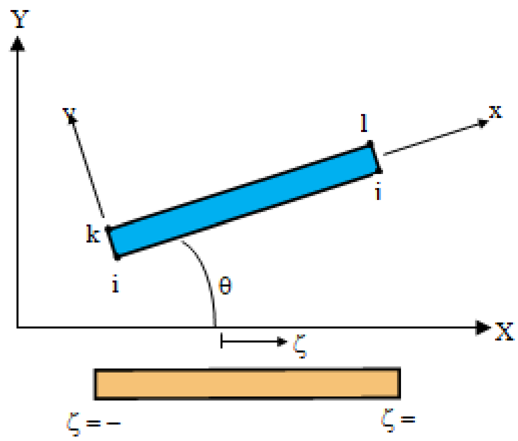

Figure 5: Interface element [1]

4. Examples

4.1 Shear transfer specimen CB2M

The composite shear transfer specimen CB2M, tested by Mattock [12], was cast in two stages. The interface between the two concretes lying in the shear plane. The first part of this specimen was three days old when the second part was cast. The interface was deliberately roughened to amplitude of 6 mm (¼ in.) to conform to the requirements of the ACI Code. An effort was made to obtain good bond between the two concretes by cleaning and wetting the first cast concrete surface. Details of the specimen is shown in Figure 6. It is designed to be gripped by friction on faces. The 32260 mm^2 (50 in^2.) shear plane is subjected to shear without moment. The shear transfer reinforcement was in the form of closed stirrups, which wrapped around longitudinal reinforcement so as to ensure positive anchorage on both sides of the shear plane. Additional reinforcement was provided to prevent failure of the specimen away from the shear plane; details of the specimen geometry and reinforcement are shown in Figure 6. The specimen was cracked in the shear plane before being subjected to shear loading.

The specimen was tested in the specially constructed two-part frame. Opposite sides of the specimen were attached to the parts of the frame by gripping plates. The shearing forces were provided by the diagonally opposed pairs of 266880 N (60 kips) capacity hydraulic center hole rams. Failure was considered to have occurred when the shear could not be increased further and both slip and separation increased rapidly.

The specimen model in Figure 6 consists of 144 four-node isoparametric quadrilateral concrete elements. The reinforcement is represented with 108 truss bar elements. 18 linkage elements are used to link stirrup reinforcement bars to concrete elements, while other bars are perfectly bonded to concrete elements. The shear plane is represented with 9 shear-transfer interface elements.

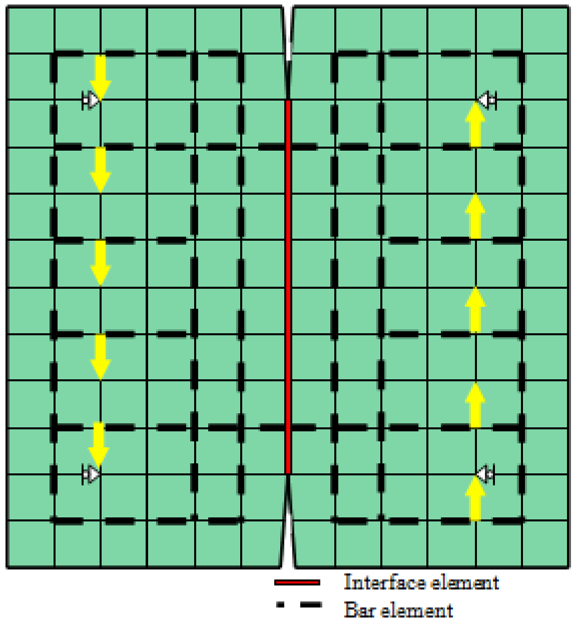

Figure 6: Finite element modeling for specimen CB2M

The analytical response of the shear transfer specimen CB2M is compared with the experimental measurements of Mattock in Figure 7. The results obtained by finite element analysis agree well with the experimental response of the specimen.

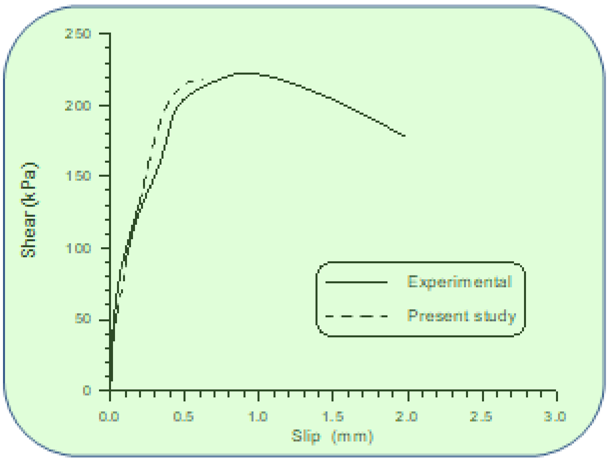

Figure 7: Comparison between experimental and analytical response of shear transfer specimen CB2M

Figure 8 shows a comparison between the experimental response of the composite initially cracked shear transfer specimen CB2M and the response of the monolithic initially cracked shear transfer specimen MN2M tested by Mattock too. It can be seen that under monotonic loading the behavior and strength of the initially cracked composite specimens with good bond at the interface, was very similar to that of the initially cracked, monolithic concrete specimens.

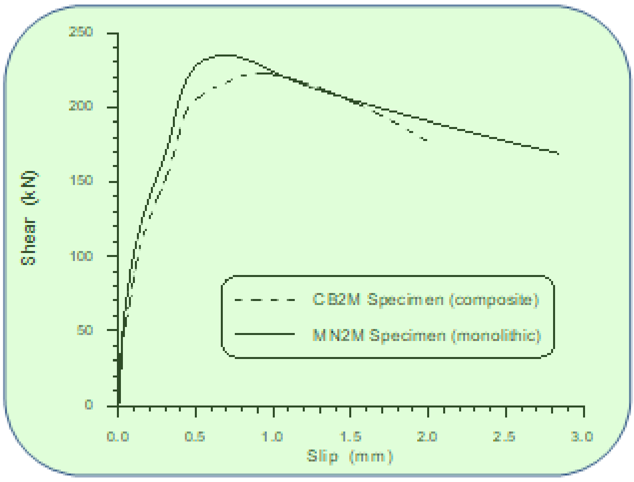

Figure 8: Comparison between experimental response of composite specimen CB2M and monolithic specimen MN2M

4.2 Revesz tests

Preliminary tests were made by Revesz [18] at the Imperical Collage of Science and Technology London University, London, England, on composite T-beams of 4.267 m (14 ft) span to determine the behavior of the beams under loads. The section of the test beam is shown in Figure 9. The particular shape of the section was chosen so as to represent a strip of a floor construction.

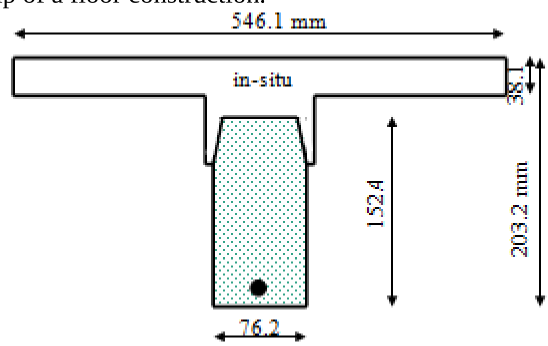

Figure 9: Section of test beam [18]

Yield point of the mild steel was found to be 268 MPa. No provision had been made for stirrups, or serration at the top of the precast beam. Age of concrete of cast-in-place flange and precast web at time of test was 7 days and 29 days, respectively. The test load was applied at third-points of the span.

Due to the symmetry in both geometry and loading, only half of the beam is considered in the finite element idealization by introducing the appropriate boundary conditions along the beam centerline.

The concrete is idealized by using 420 four-noded rectangular elements as shown in Figure 10. The reinforcement is represented by 70 bar elements, connecting with concrete elements by 71 bond-slip linkage elements. Surface between the two concretes is idealized by 70 shear-transfer interface elements.

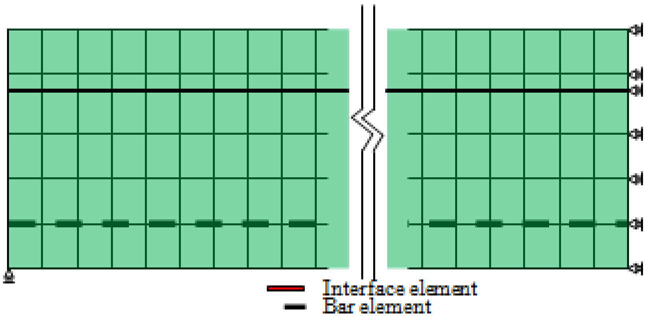

Figure 10: Finite element discretization of the beam tested by Revesz

Figure 11 represents the load mid-span deflection curve of the beam considered. Comparison with experimental results indicates a close agreement till about 80% of the ultimate load. A stiffer behavior of the theoretical model was observed during the next load increments. This discrepancy of results may be reasoned due to the tension stiffening adopted in this research which is not suitable for poor reinforced concrete. However, since this phenomenon only produce secondary effects, the analytical ultimate load level (382 kN) is detected quite well compared with the experimentally observed of 379.4 kN, with an error of only 0.7%.

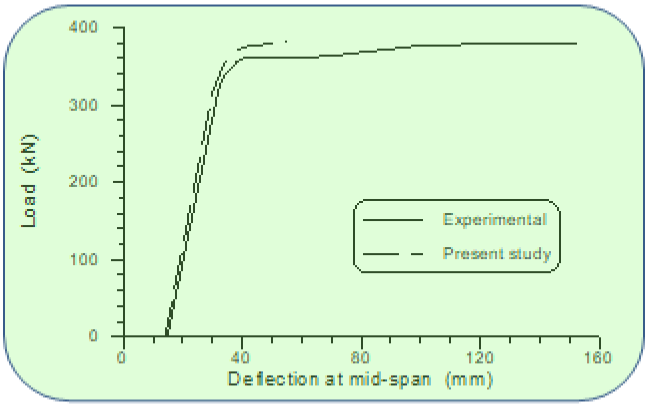

Figure 11: Load mid-span deflection curve of the beam tested by Revesz

5. Conclusions

The following conclusions can be drawn from the present study:

1) A good estimation for the analysis and the ultimate load of the friction interface between two concretes, which may contribute in more practical design applications.
2) The performance of the linkage element and the interface element, used in this study to model dowel action and shear transfer, respectively, between two concretes cast in different times, is quite good.

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