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Numerical Investigations to Evaluate the Interfacial Shear Strength of Concrete Composite Members

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Abstract: **— Concrete composite slabs with precast concrete deck and cast-in-place topping is used extensively in construction industry now a day as it reduces the construction time, eliminates the formwork usage and ensures good quality of construction. The composite action between the segments depends on interfacial shear resistance between the segments which in turn depends on the interface parameters such as cohesion, friction and area of shear connectors. Push-off test is used to evaluate the interfacial shear resistance of concrete composite members. In the present study, L shaped push-off test specimen details reported in the literature is taken up for numerical investigation. A 3D solid modelling of L-shaped push-off specimen is carried out. The concrete part of the specimen is modelled using solid finite element. The material model for concrete could simulate concrete cracking, crushing, and crack closure. The fracture characteristics of concrete are modelled by an orthotropic smeared crack model based on the Rankine's theory. The reinforcement bar is modelled using line element. The material model for reinforcement steel uses a bilinear elasto-plastic model with hardening. The interface is modelled using a zero length gap element. The interface material model is based on Mohr-coulomb criteria with tension cut off. The nonlinear finite element analysis of the push-off specimen is carried out and validated with the reported results. It is found that the finite element results corroborate with the reported experimental results.**

Index Terms **- Cohesion, Interface, Push-off tests, Shear strength, Shear Friction.**

I. INTRODUCTION

Some situations exists where shear failure constrained to occur along a plane, such as in composite construction like precast slab deck and cast-in-situ concrete topping layers, precast web and cast-in-place flange composite beam. The transfer of shear across such a plane is called "shear transfer". The monolithic behaviour of these composite members depends only on the interface shear strength. At times, structures need performance improvement which necessitates repair and strengthening. Existing bridges are strengthened by a concrete overlay. Shear needs to be transferred perfectly between concrete overlay and deck slab. So, for the repair and maintenance of the structures "Shear friction mechanism" is as importance as in composite member design. This horizontal shear between two segments is resisted by the surface roughness, cohesion between two segments, and the area of shear reinforcement crossing the interface. The horizontal shear strength is evaluated experimentally using the push-off test. Push-off test could be performed with varying area of shear reinforcement across the shear plane, using different areas of shear plane, changing the angle of shear reinforcement with respect to the shear plane, using different surface roughness conditions at the shear surface. Thus, the shape and size of the push-off specimen vary depending upon the purpose of test to be performed. Push-off tests on L-shaped specimen were conducted on specimen with 1) application of line load at the shear plane with initial crack, 2) uncracked cold joint at shear plane, 3) both segments cast monolithically, 4) shear key at interface. The first concept of shear friction mechanism was published by Birkeland and Birkeland [1] in the late sixties. Birkeland and Birkeland [1] proposed that shear could be transferred across an interface by what they termed as a "shear friction". They postulated that when the two surfaces of the composite member move over another, the reinforcement crossing to interface tends to yield and the tensile force of the reinforcement compress the two faces together. By comparing the available experimental data, Birkeland and Birkeland [1] showed that the shear friction hypothesis predicted shear strength along an interface in a conservative manner. Mast [2] proposed empirical expression on the interface friction for various interface conditions such as concrete to steel connection, concrete to concrete connection with rough interface and smooth interface. From the series of experimental push-off test results Hofbeck et al. [3] showed that the dowel action of reinforcing bars crossing the shear plane provides minimal contribution to ultimate shear in initially uncracked sections but is substantial for specimens with pre-existing cracks. In initially cracked concrete, the concrete strength sets an upper limit value for area of shear reinforcement (ρFy), below which the relationship between ultimate stress (vu) and area of shear reinforcement (ρFy) is the same for concrete of strength equal to or greater than that of concrete being considered. Mattock et al. [4] explained about an externally applied compressive stress (σNX) acting transversely to the shear plane could add to the effect of parameter ρFy and proposed a design shear strength equation. Mattock et al. [5] investigated shear friction specimens with moment or tension acting across the shear plane and showed that for the elements subjected to combined moment and shear, the ultimate shear transfer capacity is not reduced as long as the applied moment does not exceed the ultimate flexural strength of the section. From the series of experimental results, Walraven [6] derived the theoretical model for the "aggregate interlock". For the first time, Loov and patnaik [7] proposed the design equation including the effect of concrete strength (F′c). Harries et al. [8] carried out a study with the high yield strength of interface reinforcing bar and analyzed the strength of the push-off specimens in pre-cracked and post-cracked stages. The result of the experimental study showed that the steel grade doesn't affect the shear carrying capacity. The steel is marginally engaged and exhibiting very less stress at the ultimate shear friction capacity.

A number of experimental studies were carried out on the push-off specimens with different concrete strengths, different steel grades of shear reinforcement, with fiber reinforced concrete, light weight aggregate concrete, and self-compacting concrete during the last few decades. Number of design equations were proposed for predicting the shear strength at interface. Very few studies were reported on the finite element analysis of push-off specimen (Barragan et al. [9], Sulllivian [10], Lavenhsgen [11], Dias-da-costa et al. [12], Nora ahmed mohmud [13]). Sullivan [9] carried out a finite element analysis on the beam specimen. Eight node quadrilateral elements were used to model the panel, girder and haunch. Three node beam elements were used to model the shear reinforcement. Three node interface elements were used to model the interface. A smeared cracking approach was used for modelling the cracks. Perfect connection was assumed between shear reinforcement and the haunch at the interface.

Dias-da-costa et al. [12] carried out the numerical study on the push-off specimen by varying the parameters namely: elastic shear stiffness; internal friction angle; dilatancy angle; cohesion; fracture energy; bond-slip relation between concrete and shear reinforcement. Concrete was considered as a linear elastic and perfectly plastic under the compression till the ultimate compressive stress is reached. The fracture energy was evaluated according to the CEB-FIP model code 1990. Initially, cohesion and friction values were estimated as per Mohr-columb failure criteria. The interface was modelled using the Mohr-columb friction law. A bond stress-slip relation between concrete and shear connectors was taken from the CEB-FIP model code 1990. Concrete was modelled by plane stress bilinear finite element and the steel connectors were modelled using the linear truss elements. The numerical simulations result is found to be in good agreement with experimental data.

Nora Ahmed Mohmud [13] carried out experimental as well as numerical investigations on the push-off specimens. Numerical modelling was done using ATENA. The 3D solid elements, CCIsoBrick with 8 nodes and CCIsoTetra with 4 nodes were used to model the concrete specimens and the steel loading plates respectively. CCBarWithBond were used to evaluate the behaviour which is in good agreement with behaviour of the corresponding tested specimens.

In the present study, numerical analysis of push-off specimen is carried out using ATENA. The interface properties such as tangential stiffness (K_{tt}), normal stiffens (K_{nn}), internal friction angle, and cohesion values are evaluated. The interface relation between vertical stiffness (K_v) and tangential stiffness (K_{tt}) values, are studied. The effect of the different cohesion values on the vertical stiffness (K_v) of push-off specimen is established. The method of modelling the interface for the push-off specimen is explained. The numerically arrived results for push-off specimen are validated with the reported experimental results.

II. NUMERICAL INVESTIGATIONS

In the present study, nonlinear finite element analyses of push-off test specimen are carried out to simulate the interface shear behaviour of composite concrete members. Nonlinear finite element program ATENA 3D is used for modelling and analyzing the push-off specimens.

1. Details of specimen chosen for study

For the evaluation of different interface properties and for the validation of numerical model with evaluated interface properties, push-off test specimen reported by Dias-da-costa [12] is chosen for the present study. The geometry of push-off specimen chosen for numerical simulation is shown in Fig. 1. The reported test specimen consists of 2, 4 and 6 number of shear connectors crossing the interface. In addition to the above, one of the push-off specimen was tested without any shear connector crossing the interface.

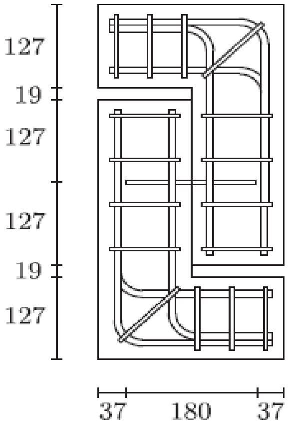

Fig. 1 Push-off specimen geometry [Dias da-costa (2012)] Dimensions are in mm

III. GEOMETRIC MODELLING AND MESHING OF L-SHAPED PUSH-OFF SPECIMEN

The geometry of push-off specimen is modelled using ten macroelements as shown in Fig.2. Each L segment is modelled using four macroelements. Two macroelements are used to model the top and bottom supporting steel plates.

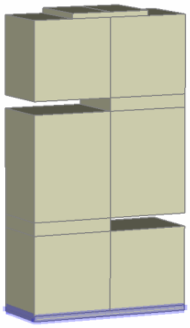

Fig. 2 Macro Modelling of concrete segments and steel plates

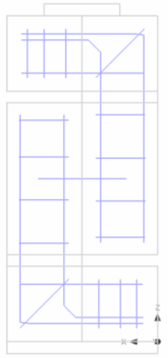

Fig.3 Modelling of steel reinforcement using line elements.

The concrete part of the specimen is modelled using 3-D solid finite element with eight nodes. The reinforcement bar is modelled using line element as shown in Fig.3. The interface is modelled using a zero length gap element. A mesh size of 15 mm is used for discretization of concrete portion of the specimen and supporting steel plate as shown in Fig.4.

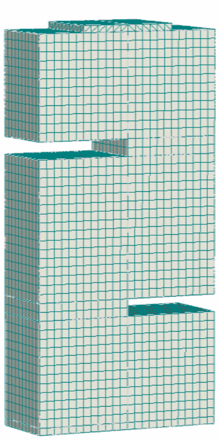

Fig. 4 Finite element mesh of the specimen

IV. MATERIAL MODEL FOR CONCRETE L-SEGMENT

A fracture- plastic model (3D Nonlinear Cementitious 2) is used for material modelling of concrete. The material model for concrete could capture following effects of concrete behaviour: 1) Nonlinear behaviour in compression including hardening and softening, 2) Fracture of concrete in tension based on the nonlinear fracture mechanics, 3) biaxial strength failure criteria, 3) Reduction of compressive strength after cracking, 4) Tension stiffening effect, 5) Reduction in shear stiffening after cracking (variable shear retention) and 6) two crack models: fixed crack direction and rotated crack direction. The material properties used for concrete are given below.

Cube compressive strength of concrete $f_c = 43$ N/mm^2
Young's Modulus of concrete = 34 GPa
Tensile Strength of concrete= 3.2 N/mm^2
Specific fracture energy concrete =1.500E-03 MN/m

2.4 Material model for support steel plates

The supporting plates are assumed as linear elastic. The Young's modulus of steel is taken as 210,000 MPa and Poisson's ratio is taken as 0.3.

2.5 Material model for reinforcement steel

Reinforcement is modeled using discrete bar approach with truss elements. Bilinear elasto-plastic material model is used for modelling of the reinforcement bars. A perfect connection is assumed between concrete and steel reinforcement bars. The material properties for steel reinforcement bar are listed below:

Young's Modulus of steel reinforcement = 210000 N/mm^2

Yield strength of steel reinforcement f_y = 450 N/mm^2

2.6 Material Model for interface

Interface material model is used to simulate contact between two surfaces. The interface material is based on Mohr-Coulomb criterion with tension cut-off. The initial failure surface corresponds to the Mohr-Columb condition with ellipsoid in tension regime (Fig.5). After stresses violate this condition, the surface collapses to a residual surface which depends on dry friction.

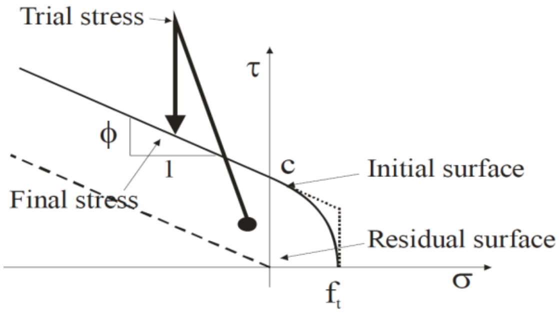

Fig. 5 Failure surface for interface Element (Červenka Consulting [18])

2.7 Boundary conditions and definition of monitoring points

The lower surface of the bottom plate is fixed in X, Y and Z directions as shown in Fig.6. The top surface of the top steel plate is fixed in Y direction.

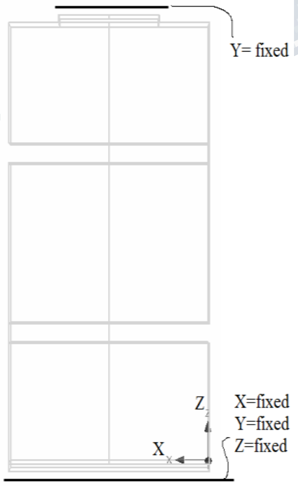

Fig. 6 Imposition of Boundary conditions

The loading to the shear plane is applied in terms of prescribed deformation. A prescribed deformation of 0.1mm is applied in load steps till the failure of the specimen. Numerical analysis is carried out in displacement control mode. Monitoring points are defined to measure the displacement response and load response. The locations of monitoring points are as shown in Fig.7. The displacement of top and bottom surfaces of top L-segment are monitored using monitoring points No. 1 and 2 assigned as shown in Fig.7. The horizontal displacements at the side face of both L-segments are monitored using two monitoring points No. 3 and 4 as shown in Fig.7. For measuring the load at each load step monitoring point No.5 is defined at the top plate center node.

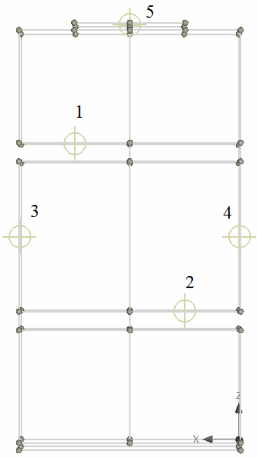

Fig. 7 Definition of five monitoring points

2.6 Solution procedure

The numerical solution is obtained by the concept of incremental step-by-step analysis using Newton Raphson method. This is an iterative method. The structural stiffness matrix is constantly updated at each iteration. The concept of solution of nonlinear equation set by Full Newton-Raphson method is depicted in Fig.8.

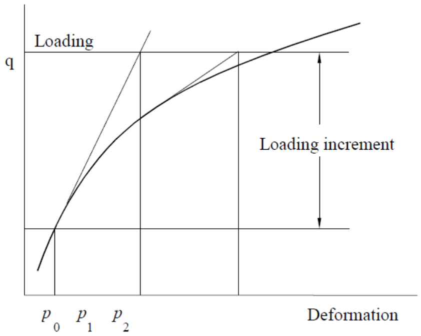

Fig. 8 Full Newton Raphson method (Červenka Consulting [18])

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V. EVALUATION OF INTERFACE PARAMETERS

In present study, the interface material model is based on Mohr-columb friction theory which in turn depends on interface properties such as cohesion, coefficient of friction, tensile strength (f_t), normal stiffness (K_{nn}) and tangential stiffness (K_{tt}). In general, the cohesion usually is defined as a function of tensile strength (f_t) of concrete and coefficient of friction (μ) is expressed as function of the roughness interface. Table 1 shows the recommended values for the cohesion and coefficient of friction (μ) by various codal provisions and reported in the literature. It is essential to highlight the fact that there is no straight forward procedure available for the evaluation of the normal stiffness (K_{nn}) and tangential stiffness (K_{tt}) values. Hence, a systematic procedure is developed to evaluate the interface tangential stiffness (K_{tt}) by relating to global vertical stiffness (K_v) of the push-off specimens.

Table 1 Cohesion and friction values

Reference	Surface type	Cohesion in N/mm^2	Co-efficient of friction
Euro code 2	Rough	$0.4f_{ctd}$	0.7
	Smooth	$0.2f_{ctd}$	0.6
	Very smooth	0.025-$0.2f_{ctd}$	0.5
ACI-318-08	Monolithic	2.75	1.4
	Rough	2.75	1
	Medium	-	0.6
Climaco and Regan [17]	Rough	$0.25(fc')^{2/3}$	1.4
	Medium	$0.25(fc')^{2/3}$	0.9
	Smooth	0.5	0.7

3.1 Variation of vertical stiffness (K_v) with tangential stiffness (K_{tt})

Using finite element analysis carried out in this study, vertical stiffness (K_v) is evaluated for different values of tangential Stiffness (K_{tt}). Tangential Stiffness (K_{tt}) values are varied from 0 to 100 N/mm^3 and corresponding vertical stiffness is evaluated using finite element analysis as shown in Fig.9. Once the relation between vertical and tangential stiffness is established, tangential stiffness (K_{tt}) corresponding to the experimentally reported vertical stiffness (K_v) of the push-off specimen could be obtained and used in finite element modelling and analyses of push-off specimens.

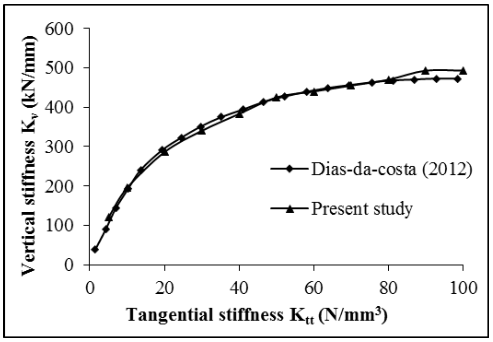

Fig. 9 Tangential Stiffness (K_{tt}) vs vertical stiffness (K_v) of Dias-da-costa specimen

In order to develop relation between tangential stiffness and vertical stiffness, it is essential to assign normal stiffness in the finite element analysis. In order to understand the effect of normal stiffness on the relation between vertical stiffness versus tangential stiffness, tangential stiffness (K_{tt}) vs vertical stiffness (K_v) curves are obtained for different values of normal stiffness as shown in Fig.10. It could be observed that relation between vertical stiffness and tangential remains almost the same for the variation of normal stiffness up to 100 N/mm^3. Hence, the value of normal stiffness less than 100 N/mm^3 could be used for the derivation of relation between tangential and vertical stiffness.

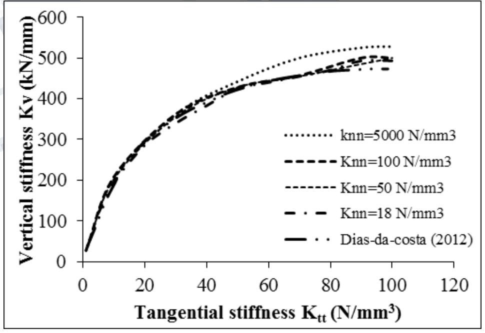

Fig.10 Tangential stiffness (K_{tt}) versus vertical stiffness (K_v) of Dias-da-costa specimen for different values of normal stiffness (K_{nn}).

3.2 Influence of normal stiffness (K_{nn}) on the maximum load carrying capacity

For evaluating the influence of the normal stiffness (K_{nn}) on the interfacial shear strength, numerical analysis is carried out for different values of normal stiffness (K_{nn}). The load versus slip relation is obtained for specimen without interface reinforcement as shown in Fig.11.Tangential stiffness value of 18 N/mm^3 as obtained from Fig.9 is used for the analysis. It is observed that with the increase of normal stiffness (K_{nn}), load carrying capacity decreases. The vertical stiffness (K_v) values are almost constant for different values of normal stiffness. The variation of maximum peak load versus normal stiffness values obtained from finite element analysis is shown in Fig 12. It is observed that the load carrying capacity is constant beyond the normal stiffness (K_{nn}) value of 100 N/mm^3. The maximum load carrying capacity is obtained for normal stiffness values between 5 to 30 N/mm^3.

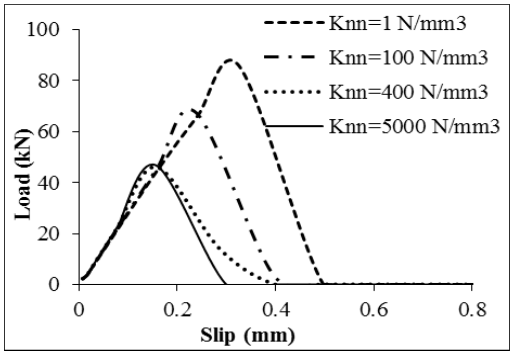

Fig.10 Normal Stiffness (K_{nn}) versus vertical stiffness (K_v) of interface

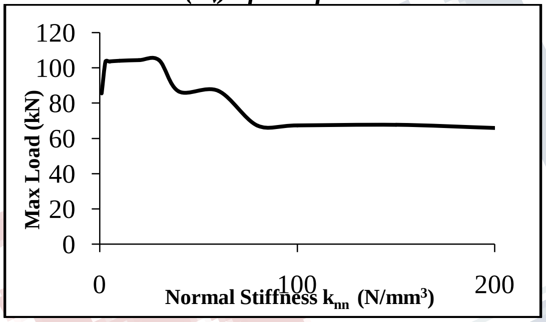

Fig.12 Normal Stiffness (K_{nn}) versus vertical stiffness (K_v) of interface

3.3 *Influence of cohesion with vertical stiffness (k_v)*

In order to get the influence of cohesion on the vertical stiffness (K_v) of the specimen, the value of cohesion is varied from 1 to 5 N/mm^2 and the corresponding load vs. displacement curves are obtained as shown in Fig.13. From Fig. 13, it may be observed that the value of vertical stiffness is independent of the cohesion. Further, it is found that with the increment of cohesion value, load carrying capacity increased. Further, the shear capacity of the plain concrete specimen could be obtained in trials by matching the numerical result with the experimental result.

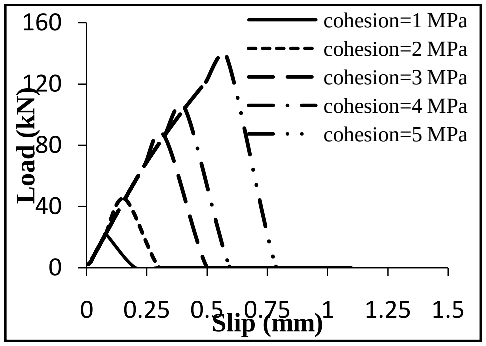

Fig. 13 Load versus slip curve for different values of cohesion

The interface parameters obtained from finite element analyses carried out in this study are as follows.
Normal Stiffness (K_{nn}) = 18 N/mm^3
Tangential Stiffness (K_{tt}) =18 N/mm^3
Cohesion = 3.8 N/mm^2

These values are used further for finite element analysis of the push-off specimens with shear connectors crossing the interface.

VI. FINITE ELEMENT ANALYSIS OF PUSH-OFF SPECIMENS WITH SHEAR CONNECTORS

Using the derived interface properties, numerical simulation has been carried out on L-shaped push-off specimen with 2, 4 and 6 number of shear connectors. For 2, 4 and 6 shear connectors crossing the shear plane, the initial curve and load carrying capacity obtained from numerical simulations are found to be in good agreement with reported experimental values. The results are shown in figs 14-16 for specimen two, four and six shear connector crossing the interface.

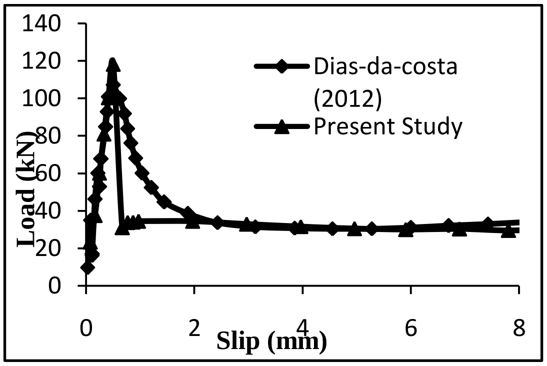

Fig. 14 Load versus slip curve for push-off specimen with 2 shear connectors

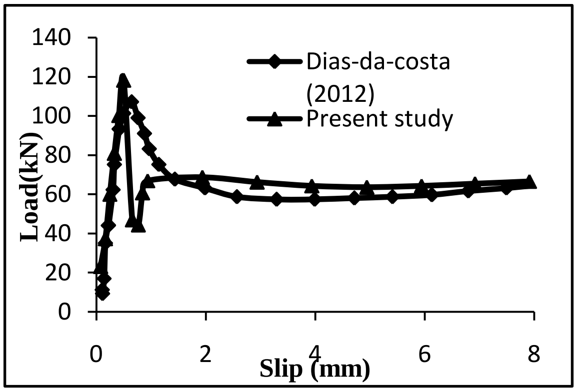

Fig. 15 Load versus slip curve for push-off specimen with 4 shear connectors

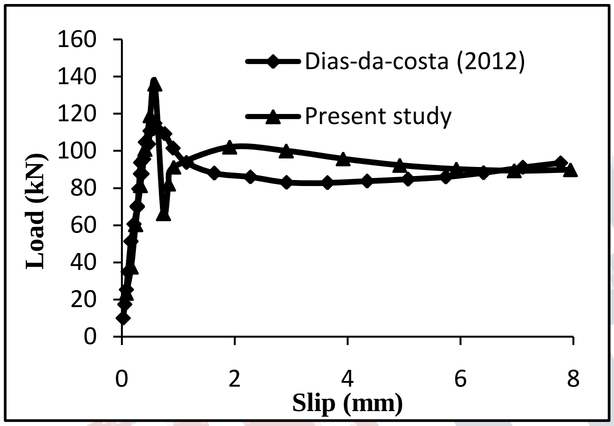

Fig. 16 Load versus slip curve for push-off specimen with 6 shear connectors

VII. CONCLUSION

The paper presents the details of finite element modelling, constitutive modelling and non-linear analyses carried out on plain concrete push-off specimens. Based on the results of nonlinear analyses carried out on plain concrete push-off specimens, it has been concluded that the vertical stiffness (K_v) of interface is independent of cohesion and normal stiffness (K_{nn}). Further, a curve of tangential stiffness (K_{tt}) versus vertical stiffness (K_v) is obtained which can be used to precisely evaluate tangential stiffness (K_{tt}) values corresponding to the given vertical stiffness (K_v). Based on the studies, it is also noted that normal stiffness (K_{nn}) within the range of 18 to 100 N/mm^3 has no influence on the vertical stiffness (K_v) but the load carrying capacity is decreased with the increase of normal stiffness (K_{nn}) values. Based on the interface parameters obtained, studies are also carried out to evaluate the shear strength of push-off specimens with different number of shear connectors. It is found that the finite element results are good agreement with the experimental results reported in the literature.

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