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ADVANCES IN STEEL CONCRETE COMPOSITE AND HYBRID STRUCTURES

[EDITED BY JY RICHARD LIEW]

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MODELING THE INTERFACIAL TRANSITION ZONE BETWEEN STEEL AND CONCRETE MATERIALS IN COMPOSITE CONSTRUCTIONS

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Abstract

The interfacial Transition Zone (ITZ) has long been recognized as the *"weak link"* in a structure. While steel materials behave relatively linear up to high stress levels, nonlinearity is a prominent characteristic of most cementitious based material. To obtain a more realistic representation to the overall behavior of composite steel-to-concrete structures, the response of the interface should be incorporated into the analysis.

A Finite Element Program written in the *Visual Basic* programming language is developed to take into account nonlinearity of the cementitious materials, while incorporating the Interfacial Transition Zone behavior. The Transition Zone is modeled as two springs, perpendicular to each other. The individual load-deformation responses of the springs were obtained from laboratory tested specimens. *The Federal Institute of Technology, Europe Model Code 2011* was used to model the cementitious material behavior. Failure criteria are analyzed based on the principal stresses at Gauss points.

Keywords: *ITZ, Spring, Stiffness Modulus, Failure Criteria.*

1. Introduction

The Interfacial Transition Zone in cementitious composite materials is widely acknowledged as to be the *"weak link"* in the structure *(Larbi, 1991)*. This weakness is due to its low adhesive strength, and the presence of calcium hydroxide crystals having an orientation that allows cracks to occur along their weak bond plane. Therefore, the stress disparity in this area will most likely be significant, and leading to crack initiation.

Due to its very small size, only around 30 to 50 µm in thickness, direct tests to obtain the ITZ properties are at this point not available. The most recent technique is the micro-indentation method, measuring the modulus of elasticity and creep from the indentation at a distance from the ITZ. Most Finite Element models represent the bond between steel and mortar by the smeared-crack method, allowing crack propagation along the ITZ surface. The constitutive model for the bond relationship is highly simplified *(Lowes et. al., 2004; Jendele and Cervenka, 2006)*.

A model representing the ITZ as a linkage element is constructed. The link consists of two springs, one perpendicular, and one parallel to the ITZ surface characterizing the normal and shear behavior (Figure 1). The linkage element is connected by two nodes, one on the steel material surface, denoted as *"s"* and one at the mortar element denoted by *"m"*. The nodes have two degrees of freedom each.

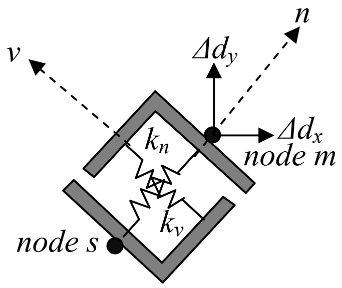

Figure 1: Linkage element model for the ITZ

The stiffness modulus of the springs k_n and k_v are expressed in their *load - displacement* response, obtained by individual laboratory tests *(Han and Nuroji, 2010; Han and Sabdono, 2011)*. When stresses increase, the relative displacements are converted to the coordinate system of the linkage element to update the stiffness modulus. Due to the highly nonlinear nature of the cementitious material and the ITZ, the *Riks-Wempners* arc-length iteration technique is accessed, to accommodate this behavior.

2. ITZ Behavior

Since the relative displacement of the two adjacent nodes of the linkage element represents the behavior of the springs, these displacements should be transformed from the global coordinate system *(X, Y)* to the local coordinate system *(n, v)* enabling evaluation and incorporation into the FEM. The local coordinate system is demarcated at the bisection line of the angle between the two ITZ surfaces, at the steel elements (Figure 2).

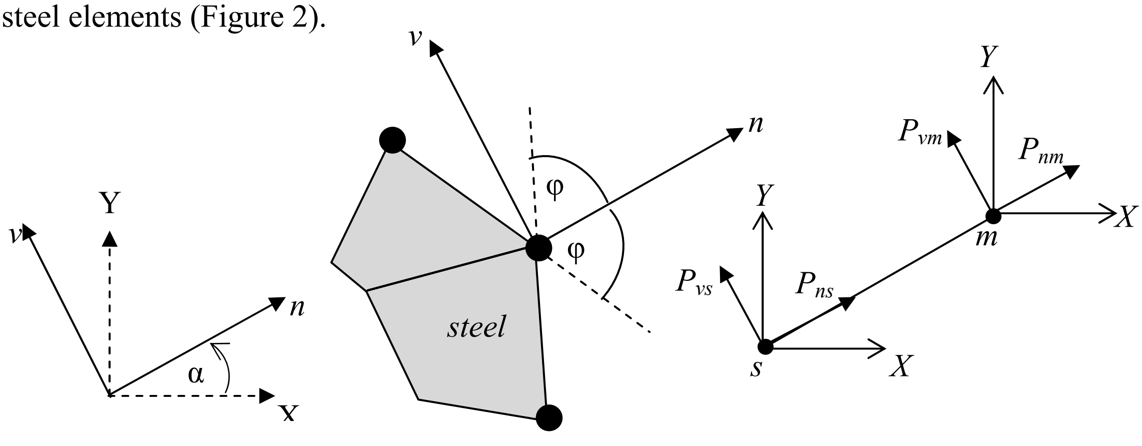

Figure 2: System transformation and algorithms

Assuming a linear, independent relationship, the behavior of the linkage element in the global coordinate system is expressed as:

$$\begin{bmatrix} P_{xa} \\ P_{ya} \\ P_{xm} \\ P_{ym} \end{bmatrix} = [R]^T \begin{bmatrix} -k_n & 0 & k_n & 0 \\ 0 & -k_v & 0 & k_v \\ k_n & 0 & -k_n & 0 \\ 0 & k_v & 0 & -k_v \end{bmatrix} [R] \begin{bmatrix} \Delta d_{xa} \\ \Delta d_{ya} \\ \Delta d_{xm} \\ \Delta d_{ym} \end{bmatrix} \tag{1}$$

Where:

[P]	:	is the force matrix of the link in the global coordinate system
[Δd]	:	is the nodal displacement matrix in the global coordinate system
[R]	:	is the transformation matrix from the local to the global coordinates system as a function of α
α	:	is the angel between the local and global coordinate system following the right-hand rule
k_n and k_v	:	are the stiffness modulus of the ITZ

The load-displacement responses are obtained through specific developed test methods, and are defined by a series of factors such as the *roughness of the steel-surface*, *the mechanical properties of the mortar*, *the water cement ratio* and the *presence of bleeding* in the ITZ. Generally, the response in the normal direction is characterized by a polynomial to the second degree. The curve shows a distinctively non-linear behavior, even at very low loading levels. The ultimate capacity occurs due to bond failure in the ITZ (figure 3).

The *load – displacement* relationship for the ITZ in shear has a *bi-linear* function, the first part representing the stiffness modulus as a contribution of adhesion and friction, and the second being purely the result of friction. Figure 3 also shows a comparison between normal and shear responses. It can be seen that the ultimate normal displacement is low, when compared to shear capacity. It is therefore most likely that failure in the ITZ will be initiated in the tension area.

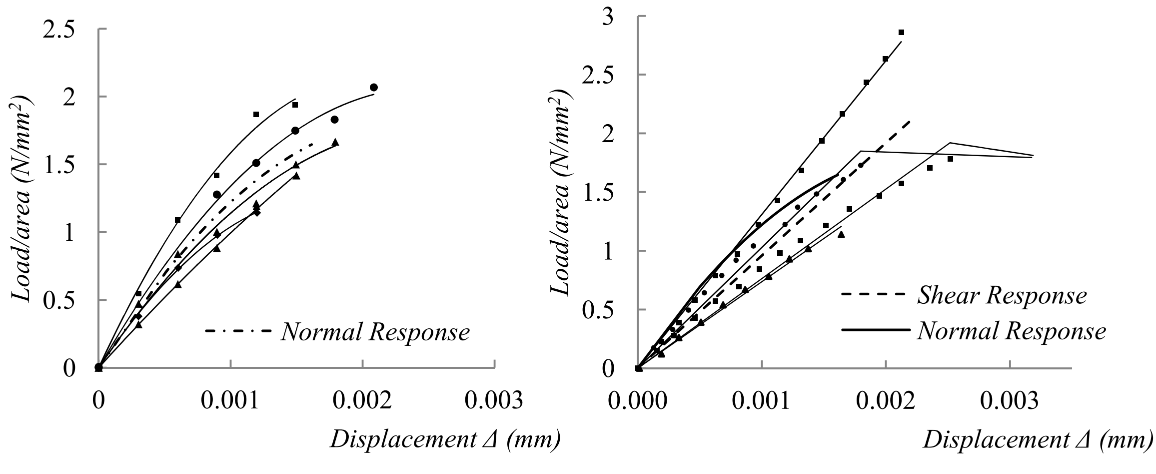

Figure 3: Linkage element stiffness modulus behavior

The stiffness modulus of the spring is a function of the relative displacement $\overrightarrow{\Delta d_{sm}}$ between the two nodes. This displacement vector $\overrightarrow{\Delta d_{sm}}$ can be determined from the displacements of nodes in the global coordinate system (figure 4).

The direction of the $\overrightarrow{\Delta d_n}$ vector is used as criterion in the analysis of the ITZ. When this vector moves in the positive direction, the normal spring is in tension and the stiffness of this spring will decrease as a function of the load increase. But when the vector moves in the negative direction, the spring is in compression, resulting in a fully bonded condition. The corresponding stiffness will therefore be infinitely large approaching ∞, and it is assumed that the two nodes s and m will coincide, thus further having identical displacements throughout the loading process. The positive *n* axis is considered pointing *outward* from the steel to the mortar in the ($s \rightarrow m$) direction, while the positive *v* axis is following the right hand coordinate system based on the position of *n.*

The behavior in shear is denoted by the vector $\overrightarrow{\Delta d_v}$, and analyzed *only* when the normal spring vector is in tension. Basically, the direction of this shear vector does not influence the behavior analysis, since shear is not direction sensitive.

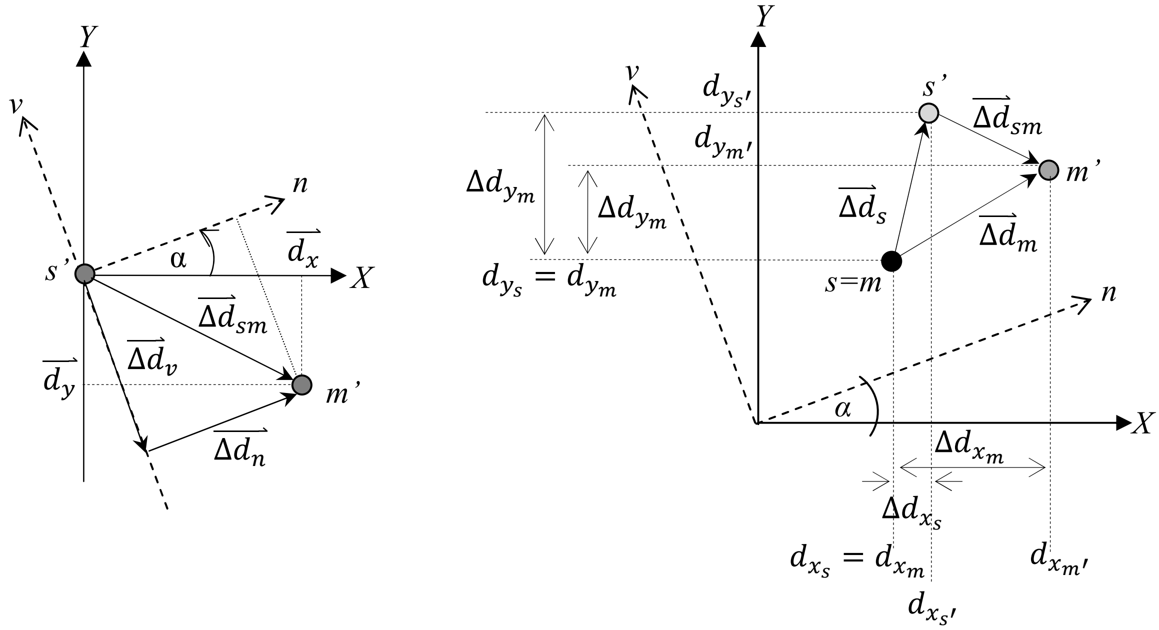

Figure 4: Linkage Element Algorithms

At initial stage, the coordinates of the linkage element nodes are identical. Double nodes are created by the mesh generator *QUAD_BUILD* version 5.0, developed in Australia, by *Dr. Alexander Tsvelikh* from *Computational Mechanics Australia Pty. Ltd.* The program itself is written in ANSI C and can be used on all Window and Unix platforms with standard C and/or C++ compilers.

To create double nodes along the ITZ, two arches or lines coinciding each other, are created. The two arches or lines need to have concurring starting and ending nodes but individually assigned, different numeration. When the arches or lines are meshed with an equal number of elements, but the area between the two arches is not defined into elements, a blank or gap in between these two arches will be created. The output of the generator is called by the *Visual Basic (Microsoft Visual Studio 2008)* program to support the Finite Element analysis. Based on preliminary studies and observing the crack pattern of the laboratory specimens, finer meshing can be placed in the areas that are most vulnerable to high principal stresses and failure.

When an increment load is applied to the system, the relative displacement between the two nodes are calculted. The algorithm for the linkage criteria becomes:

$\Delta d_n > 0$: when the spring in the normal direction is in tension (2)

$\Delta d_n \leq 0$: when the spring in the normal direction is in compression (3)

Where:

Δd_n : is the ITZ normal displacement in the local coordinate system

For the case that the normal spring is tension, two failure options are considered. First is the case where the displacement Δd_n *exceeds* the ultimate normal displacement $(d_n)_{ult}$. The bond in the normal direction then drops to zero. However, since the shear capacity is much higher than the normal capacity, the k_v will still remain in the equation and ITZ failure is due to *tension*. Secondly is the case were shear-displacement Δd_v surpasses the ultimate shear displacement. In this case the ITZ will fail in *shear*.

When the stiffness matrix of the linkage element reaches zero, the bond within the ITZ has vanished and this will result in a physical gap in the ITZ. During testing of the laboratory specimens, the development of this gap can clearly be observed. For the condition of a linkage element in compression, a significantly large number in the order of the 15th exponent is assigned to the stiffness k_n and k_v.

The direction of the positive normal coordinate *n* in the local system is determined by the vector approach. The vectors between the two adjacent notes are converted to a unity vector *[R][i,j],* and their resultant calculated. The coefficient of this resultant vector is converted to the opposite direction by applying a negative sign to the *[i,j]* matrix (Figure 5.).

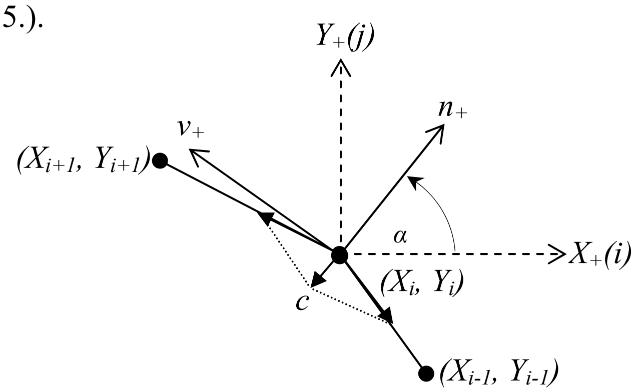

Figure 5: Unity vector system for determination of local coordinates

$$[R] = \begin{bmatrix} x_{i+1} - x_i \\ y_{i+1} - y_i \end{bmatrix} \quad (4)$$

$$d = \sqrt{[R]^T[R]} \quad (5)$$

$$[n] = -[c] = -\sum \frac{1}{d}[R]^T \begin{bmatrix} i \\ j \end{bmatrix} \quad (6)$$

Where:

$[R]$: is the vector coefficient between ITZ nodes

d : is the length between two adjacent nodes

c : is the resultant of the unit vectors

$\begin{bmatrix} i \\ j \end{bmatrix}$: is the unity vector

3. Material Nonlinearity and Iteration Procedure

The mortar is analyzed based on the *Kupfer-Hilsdorf-Rusch (1969)* failure envelope. When principal stresses at Gauss points are falling *within* the envelope boundaries, no failure occur and the material stiffness modulus and Poisson's ratio are updated accordingly *(Han and Purnomo, 2011)*. The behavior of material under biaxial stresses is approach by the *CEB-FIB Bulletin Nr. 42, 2008.* For sign convention, the stresses and strains are considered negative in compression, and positive in tension. The Poisson's ratio υ_c is a function of the nonlinearity index β, derived from *Ottosen (1979).*

Nonlinearity of the material is approached by the *arc-length iteration method*. This iteration procedure becomes necessary since the stiffness calculated at the former loading stage, will produce a load-error in predicting the actual loading at the next increment. Iteration is conducted by a correction procedure to minimize this error.

The arc-length method performs an iteration *along* an arc, drawn from the calculated external loading point to its intersection with the actual load-displacement curve. The last convergence state on this curve, functions as origin to the arc. *Riks and Wempner* (*Riks, 1970; Wempner, 1971*) developed an algorithm to simplify the mathematical expressions, and used the vector approach to replace the arc with a vector $\overrightarrow{n_\iota}$ perpendicular to the vector $\overrightarrow{t_\iota}$ which is a product of the load and displacement vectors $\overrightarrow{\Delta P_\iota}$ and $\overrightarrow{\Delta d_\iota}$. The arc-length method has the advantage that a descending branch of a curve can be incorporated into the analysis, without resulting in an error in the calculations due to negative values of the stiffness modulus.

4. Results and Discussion

The model is run for a mortar cube 100 x 100 x 50 mm, having single cylindrical steel inclusions, 45 mm in diameter. The mechanical properties of the mortar, steel and ITZ are obtained from laboratory tested specimens and listed in Table 1.

Table 1: Material properties

Properties	***Mortar***	***Steel Inclusion***	***ITZ Normal Response***	***ITZ Shear Response***
Compression Stress f'c (MPa)	17.44			
Tensile Yield Stress f_t (MPa)		583.3		
Modulus of Elasticity E (Gpa)	25.88	211.17		
Poisson's Ratio υ	0.224			
Initial Stiffness (N/mm²/mm)			1549.02	959.24
Ultimate Strain			0.00161	0.00202
A Coefficient $(y = A\,x^2 + B)$			-327718	

The laboratory specimen was tested with a constant incremental displacement. The FEM program was run to compare the influence of the ITZ to the overall structures behavior. Figure 6 shows the load-displacement responses for the structure neglecting the ITZ, and including the linkage element representing the ITZ. It is shown that a lower stiffness modulus is obtained when the behavior of the ITZ is included.

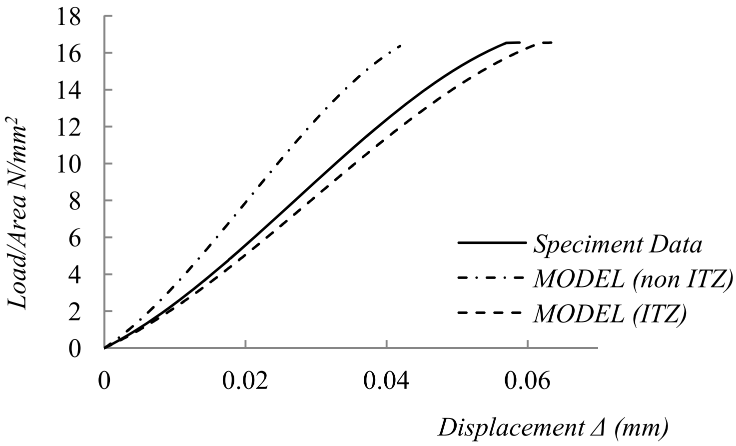

Figure 6: Load-displacement response for the ITZ

The FE model assuming a fully bonded condition, *without* the presence of the ITZ results in a higher stiffness modulus at every loading stage, when compared to the model incorporating the ITZ for the same loading levels. The model also over predicts the actual behavior of the laboratory tested specimen, significantly. While the ultimate capacity was estimated closely by both the models, the FE model with the ITZ demonstrated a slightly lower stiffness when compared to the laboratory specimen.

As for the ductility, it can be seen that neglecting the ITZ will predict a much lower value, resulting in a less ductile structure. However, the load-displacement curves of FEM and laboratory specimen are identical, following a non-linear response, even at low loading stages. The parabolic curve reaches a maximum, and demonstrates a very slight descending branch, up till failure.

5. Conclusion and Further Research

The presence of the ITZ in the analysis of composite structures and material could not be neglected. The developed FEM program modeling the ITZ as a linkage element is therefore most useful to obtain a more realistic and accurate prediction of the load-displacement response. This program will also include the nonlinear nature of the cementitious material.

The load-displacement relationship for the normal and shear response is assumed linear and independent, this is not totally true. Also, the statement that in compression the ITZ is fully bonded and no shear displacement occurs is an understatement to the actual behavior. To overcome these simplifications, more accurate and realistic laboratory test method for the ITZ should be developed. The shear response as a function of the normal stress, both in tension or in compression should be studied. From here on, the stiffness matrix of the ITZ could be constructed reflecting the interaction between shear and normal behavior. In the special case of bar reinforcement, the shear behavior can be approached by the constitutive model representing the bond between the bar and the concrete.

The FEM program is operated using the full, square matrix based on the Gauss elimination method. When dealing with more complicated configurations, for example deformed steel bars that requires very fine, complex meshing, the band-width method should be accessed enabling a shorter running time.

A sensitivity analysis including the effect of loading increments and meshing should be conducted, to test the accuracy and effectiveness of the developed program. More elaborate laboratory test specimens will be used to validate the outcome, for various types of mortar mixes, and diversity in steel properties. The outcome of these validations and sensitivity analysis will be used to improve and correct the ITZ program.

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