

STRUCTURE-STRUCTURE INTERACTION IN THE REINFORCED CONCRETE FRAMES-WALL

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ABSTRACT

Reinforced concrete frame-wall (RC frame-Wall) structures are generally solved in a global manner by modeling the entire structure by assembling the RC frame and wall stiffness matrices into a global matrix. The bar-wall element interface is modeled at the mean line of the beam-column element, according to RPA 99, which limits the interaction to the axial and transverse components of the forces (mechanical and kinematic) thus neglecting the effects of section rotations.

In order to take into account, the rotational components of the mechanical behavior of the beams (section rotation and bending moment), the interaction between the RC frame and the wall must take place at the real interface of the two substructures, i.e. at the extreme fiber of the bar elements (beams and columns). The transmission of force from the wall to the RC frame is done by transforming the tangent stresses of the wall into moment in the beam.

1. INTRODUCTION

Interactions between different systems are particularly studied in fluid-solid interactions (Miguel, 2009; Javanshir, 2021) or soil-structure (Al-Tameemi, 2023; Long 2021) cases. Finite element calculation methods use models to construct large global matrices to then begin the direct resolution process. However, the use of the sub-matrix calculation method requires indirect or iterative resolution methods by block.

Simplified methods for calculating the response to horizontal loads of mixed structures exist in the literature. Numerical analysis is performed on wall shear joints (Casagrande, 2015) or on structural discontinuities, frame-wall or beam-column (Nollet, 1991; Dipali, 2015; Nouali, 2017).

This paper simulates the behavior of a reinforced concrete frame structure by having the two substructures (the RCF on one side and the wall on the other) interact separately at the extreme fibers of the interacting RCF elements. The theory is first constructed, for two interacting substructures across a geometric interface, in the linear elastic domain. The method is then solved by establishing a convergent numerical scheme by applying the principle of conservation of mechanical energy. The interaction between two structures is established by equalizing the stresses and displacements at the interface Γ (Fig. 1). The principle consists in modeling the reaction of a structure submitted to a stress of the other structure at the interface (Chaboche, 2001).

In general, the equilibrium of the two structures is that of the mutual action-reaction forces on the interaction interface Γ described by the following equation (1):

$$\overline{\sigma}_1 \cdot \vec{n}_1 + \overline{\sigma}_2 \cdot \vec{n}_2 = \vec{t}_1 + \vec{t}_2 = \vec{0} \quad (1)$$

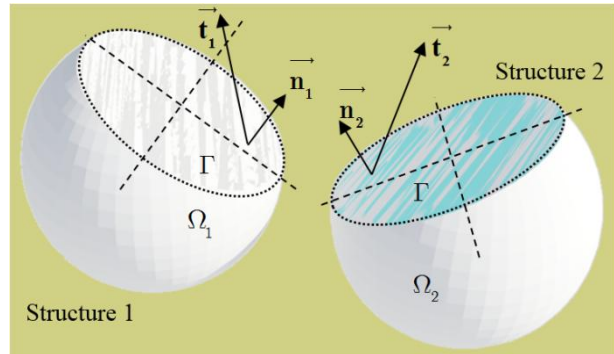


Figure 1. Representation of the structure-structure interaction on the interface Γ

2. STRUCTURE-STRUCTURE COUPLING

Mechanical structures in static equilibrium are governed by a system of partial differential equations with associated boundary conditions (eq. 2 and 3). These equations describe the mechanical behavior of each structure separately:

Substructure N°1:

$$\begin{aligned} \text{div} \overline{\sigma}_1 + \vec{f}_1 &= \vec{0} \quad \text{on } \Omega_1 \\ \hat{u}_1 &= u_{01} \quad \text{on } \Gamma_{1,D} \\ \vec{q}_1 &= \overline{\sigma}_1 \cdot \vec{n}_1 \quad \text{on } \Gamma_{1,q} \end{aligned} \quad (2)$$

Substructure N°2:

$$\begin{aligned} \text{div} \overline{\sigma}_2 + \vec{f}_2 &= \vec{0} \quad \text{on } \Omega_2 \\ \hat{u}_2 &= u_{02} \quad \text{on } \Gamma_{2,D} \\ \vec{q}_2 &= \overline{\sigma}_2 \cdot \vec{n}_2 \quad \text{on } \Gamma_{2,q} \end{aligned} \quad (3)$$

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The interaction condition by equalizing the kinematic and mechanical state at the interface of the two substructures (Miguel, 2009) is added to equations (2) and (3):

$$\begin{aligned} \overline{\sigma_1} \cdot \overline{n_1} + \overline{\sigma_2} \cdot \overline{n_2} &= \overline{t_1} + \overline{t_2} = \overline{0} \text{ on } \Gamma \\ \overline{u_1} &= \overline{u_2} \end{aligned} \quad (4)$$

The solution to this system of equations is a field $\mathbf{U}_1$ defined on Ω_1 and a field $\mathbf{U}_2$ defined on Ω_2 . It is clear that the field $\mathbf{U}_1 \oplus \mathbf{U}_2$ is continuous on $\Gamma = \Omega_1 \cap \Omega_2$.

2.1 Mathematic description

The systems (2) and (3) completed by the system of equations (4) can be reduced to the study of the interaction at the interface $\Gamma = \Omega_1 \cap \Omega_2$. After transforming the systems into their algebraic equivalent by finite element discretization, the continuous quantities such as displacement fields and force fields become displacement vectors and force vectors applied to the nodes of the meshes, in particular, the stress vectors $\overline{t_1}$ and $\overline{t_2}$ integrated on the interface Γ are transformed into discrete fields of nodal forces $\mathbf{F}_1$ and $\mathbf{F}_2$ (Zienkiewicz, 2013).

Let be two elastic structures S_1 and S_2 , interacting on the interface Γ with kinematic conditions and admitting a compatible and continuous displacement field on the interface. An operator is defined which allows to transform a force field $\mathbf{F}$ into a displacement field $\mathbf{u}$. This force field is defined on the interface Γ on which is also defined the displacement field $\mathbf{u}$ (equation 5), which is a reduction of the displacement field $\mathbf{U}$ of Ω on Γ .

$$\begin{aligned} \mathbf{u}_1 &= \mathcal{A}_1(\mathbf{Q}_1, \mathbf{F}_1) \\ \mathbf{u}_2 &= \mathcal{A}_2(\mathbf{Q}_2, \mathbf{F}_2) \end{aligned} \quad (5)$$

With:

$\mathbf{u}_1$ and $\mathbf{u}_2$ are the discrete reductions of the fields $\mathbf{U}_1$ and $\mathbf{U}_2$ on the interface,

$\mathbf{Q}_1$ and $\mathbf{Q}_2$ are the static loads acting respectively on structures S_1 and S_2 ,

$\mathbf{F}_1$ and $\mathbf{F}_2$ are the discrete actions/reactions of structures S_1 and S_2 .

The aim of the problem is to find the nodal field's $\mathbf{u}_1$, $\mathbf{u}_2$, $\mathbf{F}_1$ and $\mathbf{F}_2$ (eq. 6) such that the interacting structures S_1 and S_2 are in equilibrium:

$$\mathbf{u}_1 = \mathbf{u}_2 \Rightarrow \begin{cases} \mathcal{A}_1(\mathbf{Q}_1, \mathbf{F}_1) = \mathcal{A}_2(\mathbf{Q}_2, \mathbf{F}_2) \\ \mathbf{F}_1 + \mathbf{F}_2 = \mathbf{0} \end{cases} \quad (6)$$

The 2nd equation of the system (6) expresses the equilibrium of the mutual action/reaction forces of the two substructures.

2.2 Description of operators $\mathcal{A}_1(\cdot)$ et $\mathcal{A}_2(\cdot)$

The construction of the operators $\mathcal{A}_j$, ($j=1,2$), results from the solution of the systems of equations (2) and (3) separately. Since the systems are linear elastic, their resolution is reduced to their transformation into linear and discrete algebraic systems by the finite element method, $\mathbf{U}_n = \mathbf{K}_j^{-1} \cdot \mathbf{F}_n$ where $\mathbf{K}_j^{-1}$ is the inverse of the stiffness matrix of the structure S_j , $\mathbf{U}_n$ the nodal displacement vector and $\mathbf{F}_n$ the nodal force vector composed of a static part $\mathbf{Q}_j$ of the loading and an interactive part $\mathbf{F}_j$ resulting from the interaction with the other structure. A linear application $\mathcal{S}_j$ such as $\mathbf{U}_n = \mathcal{S}_j(\mathbf{Q}_j, \mathbf{F}_j)$ that which acts on the vector $\mathbf{F}_n$ is associated with the matrix $\mathbf{K}_j^{-1}$. The operator $\mathcal{A}_j$ as defined by the system of equations (system 5) is only a

reduction of the operator $\mathcal{S}_j$, defined on the entire domain Ω_j on the interface.

2.3 Linearity and the concept of superposition

For a structure S_j , the expressions of the system of equations (system 5) can be decomposed into two superposed actions by:

$$\begin{aligned} \mathcal{A}_j(\mathbf{Q}_j, \mathbf{F}_j) &= \mathcal{A}_j(\mathbf{Q}_j, \mathbf{0}) + \mathcal{A}_j(\mathbf{0}, \mathbf{F}_j) \\ &= \mathbf{u}_{j,0} + \mathcal{B}_j(\mathbf{F}_j) = \mathbf{0} \end{aligned} \quad j = 1,2 \quad (7)$$

For structure S_1 , for example, the displacement at the interface is deduced by superposition the actions $\mathbf{Q}_1$ and $\mathbf{F}_1$. The displacement $\mathbf{u}_{1,0}$ is defined as the static part of the displacement field of the structure S_1 under the load $\mathbf{Q}_1$ and in the absence of the structure S_2 .

$$\begin{aligned} \mathbf{u}_{j,0} &= \mathcal{A}_j(\mathbf{Q}_j, \mathbf{0}) \\ \mathcal{B}_j(\mathbf{F}_j) &= \mathcal{A}_j(\mathbf{0}, \mathbf{F}_j) \end{aligned} \quad (8)$$

The operator $\mathcal{B}_j(\cdot)$ applied to the field $\mathbf{F}_j$ calculates the displacement field at the interface Γ of de Ω_j in the absence of the loading $\mathbf{Q}_j$. It is linear because $\mathcal{B}_j(\mathbf{0}) = \mathbf{0}$.

By the expressions (8), the expression (6) becomes:

$$\begin{aligned} \mathbf{u}_{1,0} + \mathcal{B}_1(\mathbf{F}_1) &= \mathbf{u}_{2,0} + \mathcal{B}_2(\mathbf{F}_2) \\ \mathbf{F}_1 &= -\mathbf{F}_2 \end{aligned} \quad (9)$$

By posing $\Delta \mathbf{u}_0 = \mathbf{u}_{2,0} - \mathbf{u}_{1,0}$ and knowing that $\mathcal{B}_2(-\mathbf{F}_1) = -\mathcal{B}_2(\mathbf{F}_1)$, the system (9) is simplified as follows:

$$\mathcal{B}_1(\mathbf{F}_1) = \Delta \mathbf{u}_0 - \mathcal{B}_2(\mathbf{F}_1) \quad (10)$$

2.4 Interpretation of $\mathcal{B}(\cdot)$ operators

In most finite element software, the access to the $\mathcal{B}_1(\cdot)$ and $\mathcal{B}_2(\cdot)$ operators is indirect because the matrices associated with these operators, which are related to the stiffness matrices, do not depend on the type of finite element chosen in the resolution. It is the global behavior of the structures, taken separately, at the interface that defines the operators. The global stiffness matrix cannot be disassembled to reduce it to a given sub-geometry. And the construction of a stiffness matrix of contiguous elements at the interface Γ represents just the localized stiffness of those elements and in no way represent the stiffness of the structure at the interface. However, the operators are inversed separately; adding them one by one, but we have no direct access to the inverse of their sum. The search of the solution for the system (10) can therefore only be obtained indirectly, i.e. by an iterative process.

2.5 Resolution method

By constructing a numerical scheme to solve equation (10) as

$$\begin{aligned} \mathcal{B}_1(\mathbf{F}_1^{i+1}) &= \Delta \mathbf{u}_0 - \mathcal{B}_2(\mathbf{F}_1^i) \\ \mathbf{F}_1^0 &= \mathbf{0} \end{aligned} \quad (11)$$

The system (11) is solved by an iterative process with an initial zero term $\mathbf{F}_1^0$. This allows us to calculate, at iteration i , the right term of the system (11):

$$\tilde{\mathbf{u}}_2^i = \Delta \mathbf{u}_0 - \mathcal{B}_2(\mathbf{F}_1^i) \quad (12)$$

Then, solve the problem of structure S_1 with as loading, the kinematic loading $\tilde{u}_2^i$ imposed on the interface Γ and deduce the interaction F_1^{i+1} by:

$$\mathcal{B}_1(F_1^{i+1}) = \tilde{u}_2^i \quad (13)$$

The process is repeated with the term F_1^{i+1} to calculate $\tilde{u}_2^{i+1}$ (system 12), until convergence. The process is stopped when the difference of the interaction F_1^i between two successive iterations is lower than a criterion chosen at the beginning, or when the energy $\delta E = E_{i+1} - E_i$ between two successive iterations is lower than a chosen limit. The energy E_i is only the work of the interaction forces, it is calculated as follows:

$$E_i = F_1^i \cdot \tilde{u}_2^i = F_1^i \cdot \Delta u_0 - F_1^i \cdot \mathcal{B}_2(F_1^i) \quad (14)$$

2.6 Convergence condition

The system of equation (11) is generally divergent because equilibrium is not assured. By introducing $F_1^{i+1} = F_1^i + \Delta F$ and taking into account the linearity of the operators $\mathcal{B}_1()$ and $\mathcal{B}_2()$, we obtain:

$$\begin{aligned} \mathcal{B}_1(F_1^i + \Delta F) &= \mathcal{B}_1(F_1^i) + \mathcal{B}_1(\Delta F) \\ &= \Delta u_0 - \mathcal{B}_2(F_1^i) \end{aligned} \quad (15)$$

Multiplying the two members of the above equation on the left by F_1^i , we obtain:

$$F_1^i \cdot \mathcal{B}_1(\Delta F) = F_1^i \cdot \Delta u_0 - F_1^i \cdot \mathcal{B}_1(F_1^i) - F_1^i \cdot \mathcal{B}_2(F_1^i) \quad (16)$$

The operators $\mathcal{B}_1()$ and $\mathcal{B}_2()$ are symmetric ($F_1^i \cdot \mathcal{B}_1(\Delta F) = \Delta F \cdot \mathcal{B}_1(F_1^i)$), so we can rewrite the above expression, noting that $\mathcal{B}_1(F_1^i) = u_1^i$ and $\mathcal{B}_2(F_1^i) = u_2^i$, as follows:

$$\Delta F \cdot u_1^i = F_1^i \cdot \Delta u_0 - F_1^i \cdot u_1^i - F_1^i \cdot u_2^i \quad (17)$$

The operators $\mathcal{B}_1()$ and $\mathcal{B}_2()$ are defined positively ($F_1^i \cdot \mathcal{B}_1(F_1^i) = F_1^i \cdot u_1^i \geq 0$), we can rewrite:

$$\Delta F \cdot u_1^i \leq F_1^i \cdot \Delta u_0 - F_1^i \cdot u_2^i \quad (18)$$

Expression (18) results in the convergence condition imposed on the interaction force increment ΔF (Fig. 2), which the normalization is derived from the principle of energy conservation.

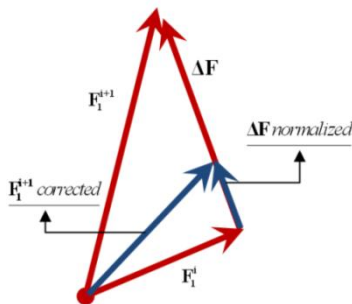


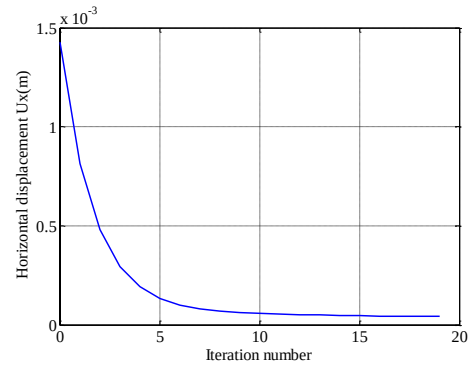
Figure 2. Normalization and correction of iterates

Expression (18) compares two scalars, the left one λ_g and the right one λ_d . Inequality (18) is restored by computing the ratio

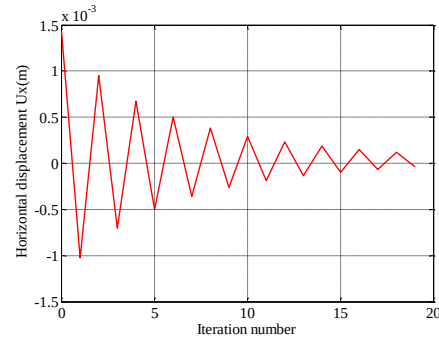
$\frac{\lambda_d}{\lambda_g}$ giving the value of the scalar by which to multiply ΔF to obtain $\Delta F_{\text{normalized}}$. The calculation of F_1^{i+1} is then given by:

$$F_1^{i+1} \text{ corrected} = F_1^i + \Delta F_{\text{normalized}} \quad (19)$$

The convergence mode can be uniform towards the equilibrium point if the correction is severe. It can be also alternated around this same point as shown in figure 3-b. If the correction is updated at each step, the convergence is fast as shown in figure 3-a.



a-correction actualized at each increment



b-constant correction chosen for all increment

Figure 3. Convergence modes to equilibrium

2.7 Algorithm and description of the calculation process

The process of obtaining the equilibrium is described in the following organigram (fig. 4).

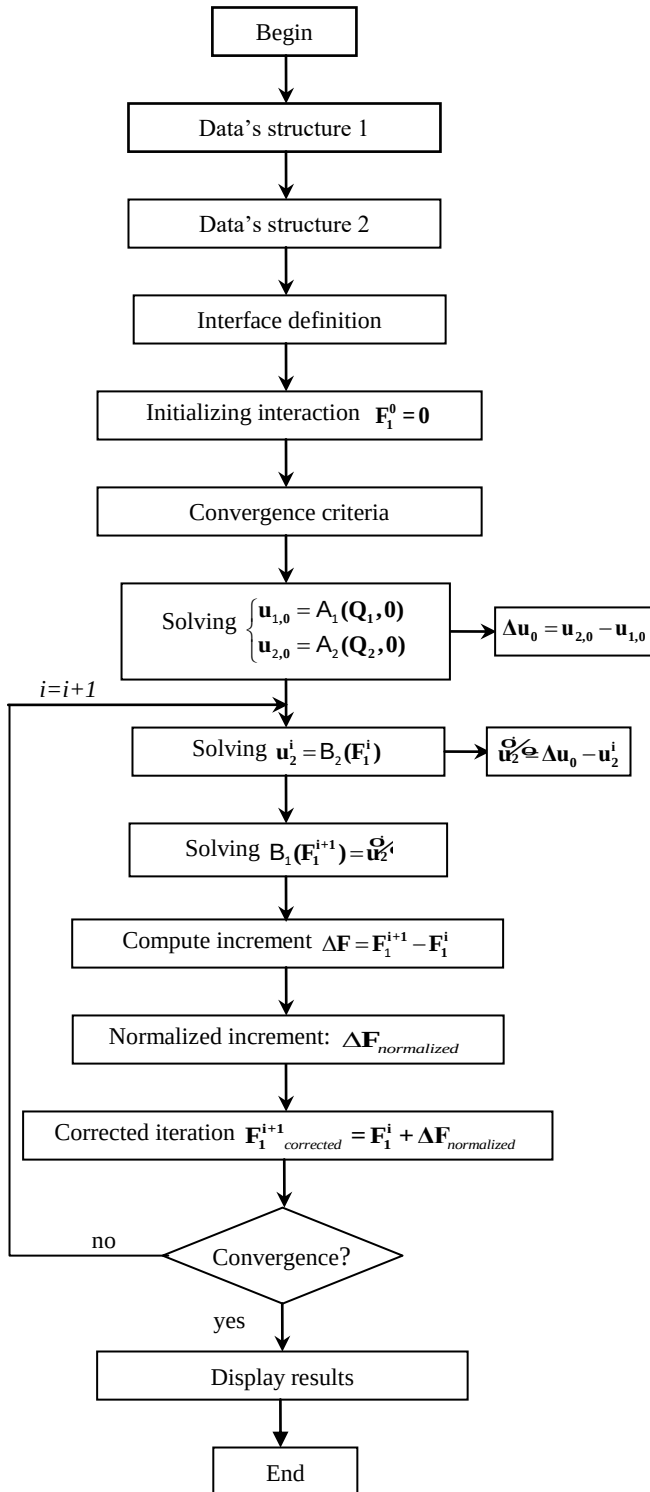


Figure 4. Organigram for obtaining the equilibrium

2.8 Interest of the method

Solving a system with a large number of degrees of freedom is slower than solving it if the stiffness matrix is subdivided into several sub-blocks taken separately. In addition, the interaction between two structures is not realistic if the ensemble of elements does not have the same algebraic and geometrical constructions. Subdividing a structure into a set of homogeneous substructures is a natural way of a scientific approach in solving complex systems and interpreting the

results. The modeling of the interaction between structures becomes possible by using homogeneous quantities on both sides of the interface. This is not the case in RCF-wall structures.

3. APPLICATION TO RCF-WALL STRUCTURES

3.1 Problem position

In the case of structures under the Algerian Seismic Code, it is accepted that structures subjected to seismic action (horizontal load) may undergo deformation in the post-elastic field. It is then resorted to methods of equivalent linear calculation, using an elastic model of the structure where the seismic action is introduced in the form of response spectrum (RPA99, 2003). In the coupling of RCF-wall structures, the equilibrium is obtained by making the two structures interact at middle lines of the beams and columns corresponding to the edges of the wall. Each of the two structures will try to prevent the other from taking its free deformation, and as a result a redistribution of forces between the two operates (Nollet, 1991; Taleb, 2017). In the case of Bernoulli type beam elements, the interaction is limited only to normal forces, ignoring shear forces (Dipali, 2015) and bending moments. Timoshenko elements solve the shear problem but not the moments (DM2S, 2001).

However, the loading conditions on the bar elements are not compatible with those on the surface elements. The forces acting on the mean line of the bars are reduced to the extreme fibers where the walls will receive them directly at the interface. This interface (figure 5) corresponds to the lower or upper fibers of the RCF structures elements. It is therefore essential to evaluate the mechanical and kinematic state of the RCF at the extreme fibers (figure 6). For a beams element in composed bending, the force reduction elements, usually expressed with respect to the center of gravity of the cross-section, will be reduced to the level of the extreme fiber of the latter in the framework of the plane section according to the following formulas:

$$\begin{Bmatrix} N \\ M \\ T \end{Bmatrix} \rightarrow \begin{Bmatrix} f_t = N - \frac{M}{v} \\ f_n = T \end{Bmatrix} \quad (20)$$

f_t and f_n are the nodal forces, respectively tangent and normal, operating at the interface of the wall. In the same way, we deduce the kinematic state as:

$$\begin{Bmatrix} u \\ w \\ \theta \end{Bmatrix} \rightarrow \begin{Bmatrix} u_t = u - \theta v \\ u_n = w \end{Bmatrix} \quad (21)$$

u_t and u_n are the nodal displacements respectively tangent and normal to the web interface.

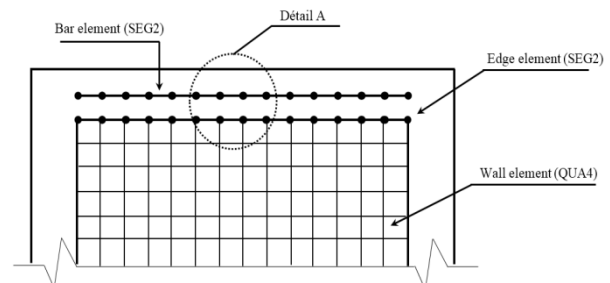


Figure 5. Graphical representation of the beam-wall interface

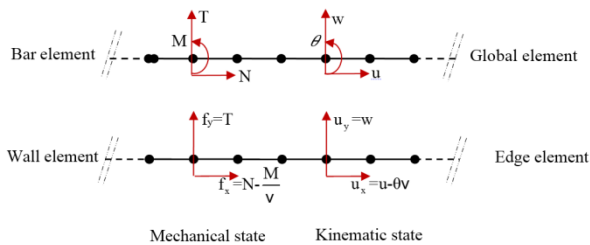


Figure 6. Representation of force vectors and displacements at interface nodes

3.2 Applications and cases of study

Several cases of study can be presented in Figure 7. The first case involves the RCF-wall interaction only at the beam level, without any interaction with the columns. In the second case, the interaction is active at the two columns only. In the third case, the interaction of the wall is with the 3 elements of the RCF structure.

In this study, this calculation strategy is applied only on the first case for the two structure-structure interaction models (Structural model with interaction structure-structure 'SMI-SS' and structural model with interaction according to the RPA 'SMI-RPA').

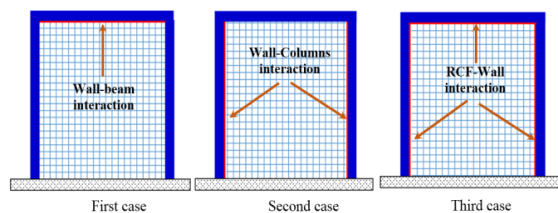


Figure 7. Cases of study

A typical typology of some existing RCF frame structure with wall in Algeria is selected as a case study: a RCF structure model with 2 frames with 4.00m of length and 2 floors with a height of 3.06m is chosen (Fig.8).

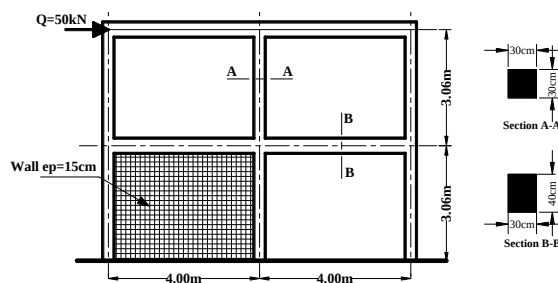


Figure 8. Geometrical characteristics and loading of the RCF-wall structure

The horizontal dispositions, the cross-sections of the structural components and the mechanical characteristics are detailed in figure 5 and Table 1 respectively.

The static loading applied to the structure simulates a horizontal seismic force (Fig.8).

RCF structure		Wall		Materials (reinforced concrete) homogenized section	
columns Section cm ²	900	Length m	3.70	Young's modulus N/m ²	3.0x10 ¹⁰

Beams section cm ²	1200	Height m	2.66	Poisson coefficient	0.2
Height story m	3.06	Thickness cm	15.0		

Table 1. Structural components and the mechanical characteristics

3.3 Structural model with interaction structure-structure (SMI-SS)

The program written on CASTEM in Gibiane language (Le Fichoux, 2001), has two procedures which transform the forces on bars into forces on the interfaces "edges of wall/extreme fibers", and inversely. Another procedure executes the same transformations on the kinematic states.

The meshes are 2-nodes segmental elements (type SEG2) for the RCF structure and 4-nodes quadrilateral elements (type QUA4) for the wall. The calculation is performed for an identical number of mesh elements for the two substructures and is fixed to 20 elements at the interface (DM2S, 2001).

3.4 Structural model with interaction according to the RPA (SMI-RPA)

RCF structures are generally solved in a global manner by modeling the entire structure by assembling the RCF structure and wall stiffness matrices into a global matrix. The bar-wall element interface is modeled at the middle line of the beam-column elements, which limits the interaction to the axial and transverse components of the forces (mechanical and kinematic) thus neglecting the effects of section rotation (RPA, 2003).

Figure 9 shows the interaction in the RCF structure and wall stiffness according to the RPA model: The middle line of the beam-column elements and the limits of wall are confused.

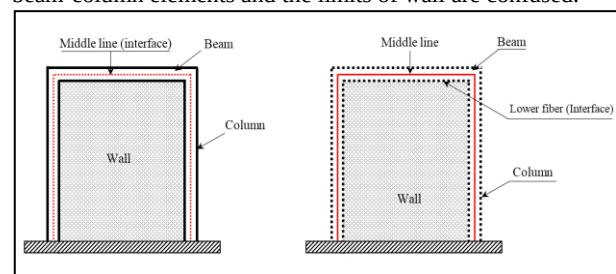


Figure 9. Interface representation according to the RPA

3.5 Results and interpretation

3.5.1 Equilibrium verification: We have previously searched the equilibrium of the structures by equalizing the mechanical and kinematic states at the interfaces. The verifications have been carried when the force increment ΔF tends towards zero with the iterations. This increment represents the differential of the nodal forces at the interface of the two substructures. In other terms, mechanical equilibrium is insured when the sum of the nodal forces of the two structures tends towards zero (Carlos, 2008).

The other aspect of the verification is the kinematic equality at the interface. This verification is inherent to the algorithm. The curves in Figure 10 show the convergence of the horizontal displacement profile at the interface (lower fiber and wall

boundary). This slow convergence is caused by the initial choice of the value of the normalization scalar.

3.5.2 Stress areas: Figures 11 to 14 represent the stress field in the case SMI-RPA and SMI-SS, with identical legends to better show the differences in their distribution, especially at the interfaces. The maximum Von-Mises stress (Fig. 11) reached is twice as large in the SMI-SS with 1.38MPa as in the SMI-RPA with 0.57MPa. This explains that the structure enters the post-elastic phase much more than it is shown in the SMI-RPA.

The maximum stresses stay almost identical for the vertical σ_{yy} component. The σ_{xx} component reaches 1.0MPa for SMI-SS against a value of 0.4MPa for the SMI-RPA (Fig. 12). The shear is also marked by a value of 0.62MPa against a value of 0.25MPa for SMI-RPA (Fig. 14).

Figures 12, 13, and 14 show marked contrasts in the distribution of horizontal, vertical, and shear stresses, depending on the SMI-SS. In contrast, the SMI-RPA shows a very smooth stress distribution.

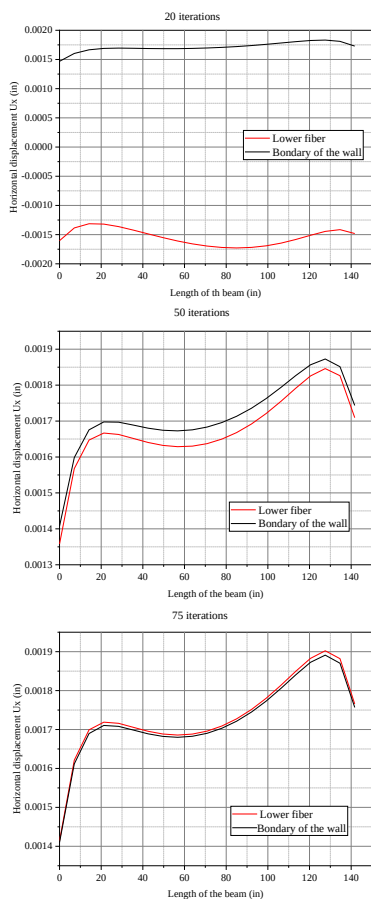


Figure 10. Kinematic equality at the interface (horizontal displacement)

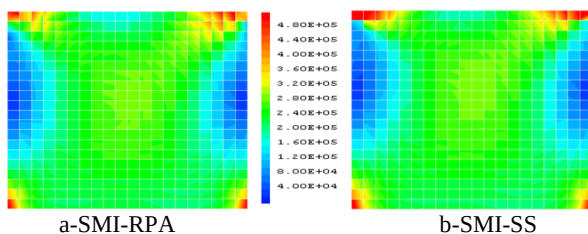


Figure 11. Von-Mises stress areas

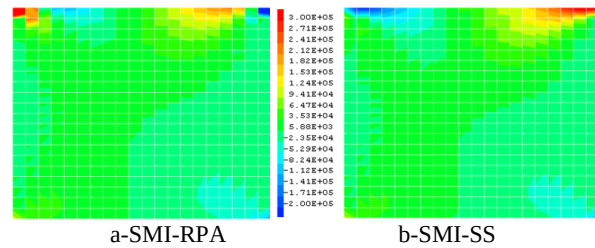


Figure 12. Horizontal stress areas

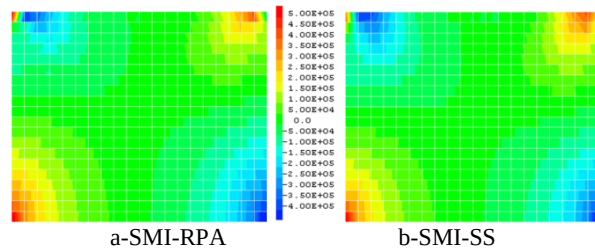


Figure 13. Vertical stress areas

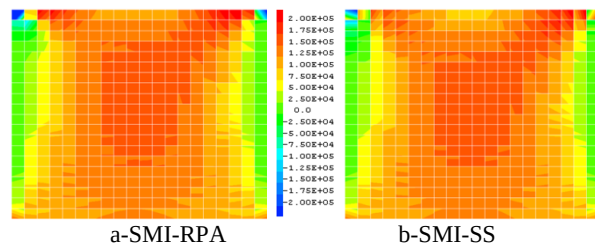
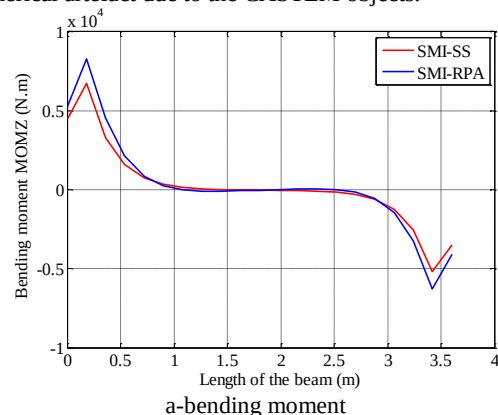


Figure 14. Shear stress areas

3.5.3 Internal efforts: Figure 15 shows some disparity in the internal forces of the interaction beam. Although the shape of the curves remains the same for both models, the SMI-RPA shows an area of very low internal forces in the bay, in contrast to the SMI-SS which shows a non-zero value for the shear force. Indeed, the existence of higher shear stresses in the wall (Fig. 14) induces higher shear forces in the beam. The bending moment shows an almost identical distribution with a slight decrease at the ends. The values at the ends of the beam are only a numerical artefact due to the CASTEM objects.



a-bending moment

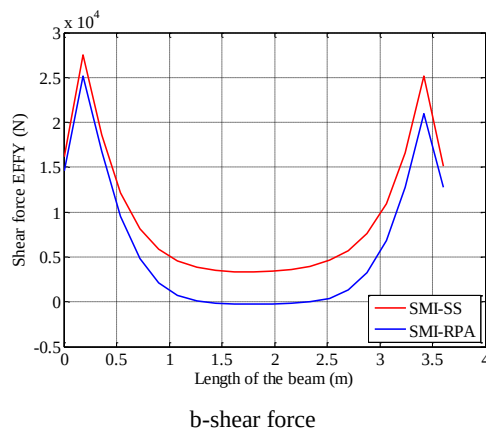


Figure 15. Internal efforts in the interaction beam

4. CONCLUSION

A theory of the structure-structure interaction was developed in order to build a numerical equilibrium search scheme. This algorithm was then applied, with the use of software CASTEM, in the case of a RCF-wall structure, whose interaction is carried out at the level of the extreme fibers of the bar elements. Then, a comparison with the model of interaction Wall-medium fibers was carried out.

Taking into account the portal-span interaction at the extreme fibers of the member-beams shows a concentration of stresses at the portal-span interfaces; this is in sharp contrast to the structural model with interaction according to the RPA (SMI-RPA). The structural model with interaction structure-structure (SMI-SS) also shows that the shear forces in the interaction beam are significant at mid-span where the SMI-RPA gives very low values.

The behavior of the wall is also different in the two models. The interaction model shows a very marked concentration of stresses at the interface. Areas of low stress also appear in this model. However, it is insufficient to limit the method to the elastic field. The development of the method to extend it in the post-elastic field becomes an ultimate aim to better the behavior of the portal frame-wall structures with a realistic modeling of the interactions.

5. NOTATION

Q_1, Q_2 : Static load of the substructure S_1 and S_2 respectively
 $u_{1,0}, u_{2,0}$: displacement of the substructures S_1 and S_2 under the static load Q_1 and Q_2 respectively.
 F_1^i : action of the substructure S_2 on the substructure S_1 at the iteration number i
 ΔF : increment force at the interface
 $\Delta F_{\text{normalized}}$: normalized increment force
 F_1^{i+1} : interaction at the iteration $(i+1)$
 $F_1^{i+1}_{\text{corrected}}$: corrected iteration

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