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# Computer Modelling of Processes of Changing over Time and Renovation of Historical Buildings

Czesław Miedzialowski<sup>1</sup>, Adam Walendziuk<sup>1</sup>

<sup>1</sup> Białystok University of Technology, 15-351 Białystok, ul. Wiejska 45E, Poland

c.miedzialowski@pb.edu.pl

**Abstract.** Building structures are continuously subjected to loads, environmental and climate influences. The effects are particularly noticeable over time in a case of historic buildings. The effects of the interaction processes are changes in a technical parameter. Structures require renovation, repairs and strengthening preceded by identification of forces and stresses in members. Apart from traditional technologies, modern materials and adhesive bonds with high strengths are used in renovation works. The paper presents an effective way of modelling and assessing the state of stresses in structures and degraded or strengthened elements using computer analyses. The developed model is based on the finite element method, significantly reducing the number of unknowns. The model can be used to identify the state of stress and strains in the design of strengthening, repairs and renovations of structures.

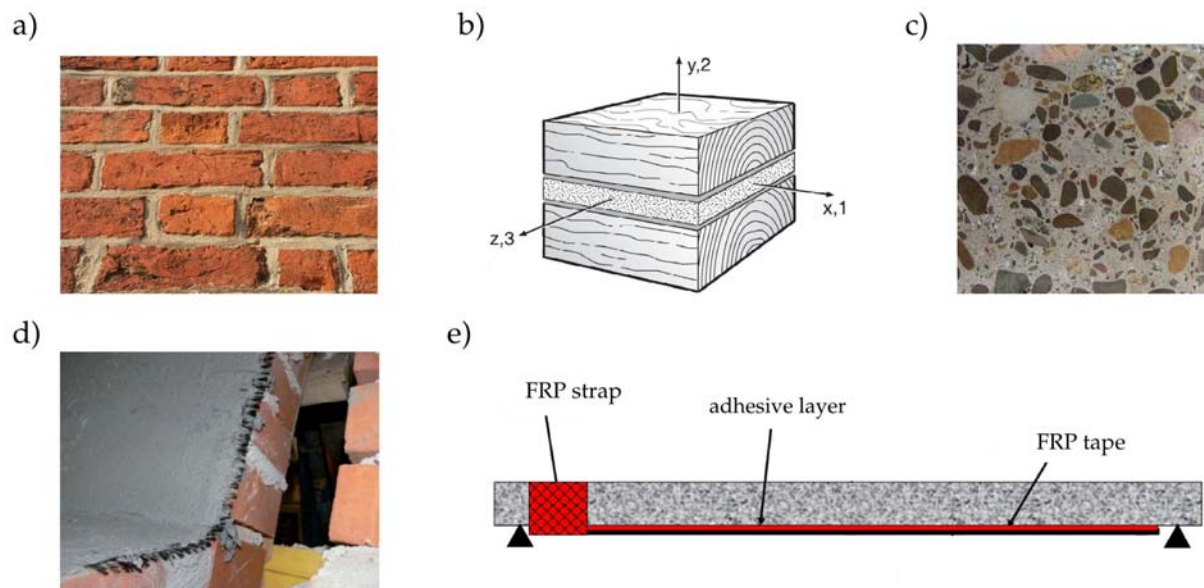
## 1. Introduction

Constructions are continuously subjected to loads, environmental and climate influences. The effects are noticeable more and more clearly over time and particularly in the case of historic buildings [1]. Loads and the interaction processes cause (induce) parameter changes and degradation of materials. Important are also structural changes introduced in the past and implemented during the use of historic buildings. In some cases, such activities may have catastrophic consequences [2]. Some historical facilities require renovation, repairs or strengthening preceded by the process of identification of forces and stresses in structural elements. The historic structures are mostly made of a combination of different materials: stone, bricks, mortar, wood. Modern adhesive materials are introduced in the renovation works along with traditional technologies [3], [4].

## 2. Heterogeneous materials and modelling

The essential feature of heterogeneous (complex) materials which is important in the analysis of phenomena in such materials under the load is the existence of connections, contacts and layers (figure 1). Approaches used in material modelling are presented in monographs e.g. [5], [6]. Scientific studies analyse and model phenomena in areas of dimensions much smaller than the structure (dimensions of the sample element, several components). The numerical determination of interactions in non-homogeneous structures is often carried out by introducing special elements in the model. Such kind of elements are referred as “zero thickness element”, contact element or interface. The use of interface elements takes into account the stiffness of the joint in the total stiffness of the modelled area. They are used in modelling, among others, joints in masonry structures [9], [10], [11], [12].





**Figure 1:** Joints of various materials: a) bricks joined with mortar, b) wood-adhesive bond [7], c) concrete d) bricks to reinforced cementitious matrix [8], e) externally bonded FRP systems

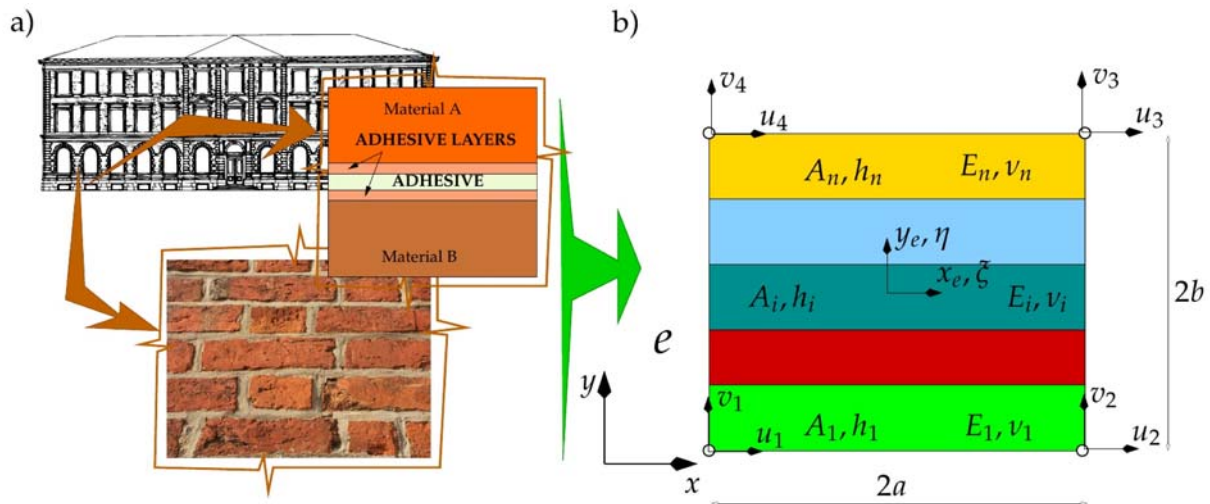
Masonry is a commonly encountered non-homogeneous construction material in historic buildings and consists of units connected by mortar. In the numerical modelling of masonry, mainly the finite element method and the discrete element method are used. Based on the finite element method, heterogeneous and homogeneous models are developed. Heterogeneous models distinguish masonry components, units, mortar and joints between them [9]. In homogeneous models masonry is assumed as a fictitious homogeneous medium and it is then possible to analyse entire structures [13]. In order to determine substitute properties various methods of homogenisation are used [14], [15]. One of the features of the modelling methods mentioned above is a large number of unknowns in the developed models, ranging from several thousands to several millions in detailed models. The paper presents an effective method of modelling and assessing the state of stress in structures and degraded or strengthened elements using numerical modelling.

### 3. The concept of heterogeneous materials modelling and degradation processes in structures

In non-homogeneous materials and complex structures subjected to stresses the damage is initiated in interface or in bonded material. An initiation of destruction in layers near joints is also observed if the contact has higher strength compared to the strength of the materials being joined. It is possible when the materials have been degraded locally or modern, durable highly adhesive materials have been used in renovation processes [4]. Since the modelling of solids using “zero-thickness” elements requires taking into account unreal and difficult to determine properties also the application of an effort criteria becomes a problem. The paper proposes a method that allows the analysis of the state of effort in such structures. Determination of stresses in non-homogeneous materials is carried out using relationships of the finite element method. The proposed model makes it possible to take into account the variability of physical parameters present in adhesive zones, substructures or degraded regions of materials.

An area is distinguished near the cohesion zones of materials with different properties and the continuity of displacements in these zones as well as in each of the constituent areas is assumed [16].

In the areas above and below the cohesion surface it is possible to distinguish  $n$  layers of certain dimensions and known material parameters, e.g. Young's modulus  $E$ , Poisson's ratio  $\nu$  (figure 2). It is further assumed that the finite element mesh of the entire multi-coherent domain is known, and the nodes are not located on the surfaces of cohesion. Displacements (unknowns) are located in nodes and



**Figure 2:** A flat layered element: a) concept, b) formulation

form a global displacement vector  $\mathbf{q}$ , consisting of nodal displacements of all elements. In the vector a number of displacements near the cohesion surfaces are distinguished, and on selected nodes the element  $e$  is defined. Node displacement components of element are ordered and form a vector:

$$\mathbf{u}_e = \{u_1, v_1, u_2, v_2, u_3, v_3, u_4, v_4\}. \quad (1)$$

A displacement field in the element is assumed to be approximated by shape functions  $N_e$  forming the matrix of shape functions:  $\mathbf{N} = [\mathbf{I}N_1 \mathbf{I}N_2 \mathbf{I}N_3 \mathbf{I}N_4]$ ,  $\mathbf{I}$  -  $2 \times 2$  unit matrix. Denoting by  $\mathbf{L}$  matrix of differential operators the deformation vector is expressed by the equation:

$$\boldsymbol{\epsilon} = \mathbf{L}\mathbf{N}\mathbf{u}_e. \quad (2)$$

Stresses  $\boldsymbol{\sigma}$  in subregions are determined according to the standard relationships of the finite element method [17], assuming in each their physical properties. Displacements of nodes are calculated using the theorem on the minimum total potential energy. It equals to the difference in energy of internal deformation and the work of external forces  $W_Q = \mathbf{q}^T \mathbf{Q}$ . The energy of internal deformation is expressed by:

$$W_\epsilon = \frac{1}{2} \int_V \boldsymbol{\epsilon}^T \boldsymbol{\sigma} dV = \frac{1}{2} \int_V \boldsymbol{\epsilon}^T \mathbf{E} \boldsymbol{\epsilon} dV = \frac{1}{2} \int_V (\mathbf{L}\mathbf{N}\mathbf{u})^T \mathbf{E} (\mathbf{L}\mathbf{N}\mathbf{u}) dV = \frac{1}{2} \mathbf{q}^T \mathbf{K} \mathbf{q}. \quad (3)$$

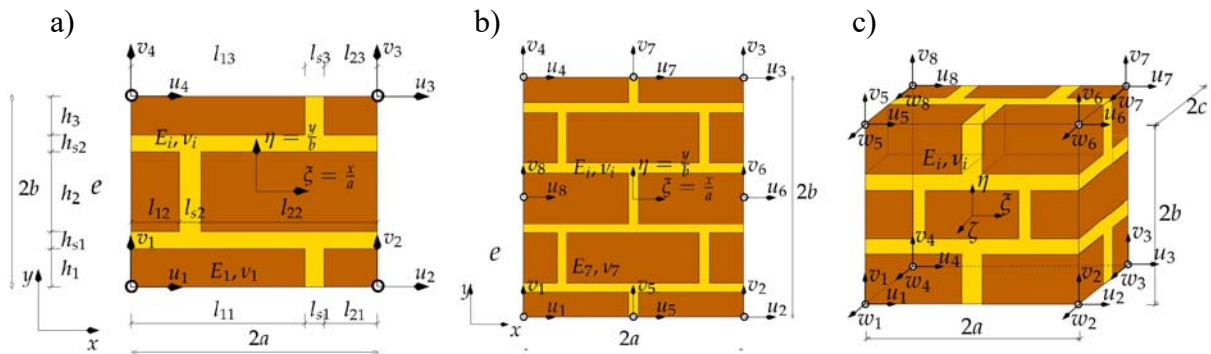
The global stiffness matrix  $\mathbf{K}$  of the system is the sum of the stiffness matrices of elements  $\mathbf{K}_e$  calculated by integrating the displacement function over element volume:

$$\mathbf{K}_e = \int_{V_e} (\mathbf{L}\mathbf{N}\mathbf{u})^T \mathbf{E} (\mathbf{L}\mathbf{N}\mathbf{u}) dV = \int_{V_e} \mathbf{B}_e^T \mathbf{E} \mathbf{B}_e dV. \quad (4)$$

According to above-mentioned assumptions, the stiffness matrix of a layered element, denoting the material thickness by  $t$  and the elastic stiffness matrix for layer  $i$  by  $\mathbf{E}^{(i)}$  is calculated as follows:

$$\mathbf{K}_e = t \int_{A_1} \mathbf{B}^T \mathbf{E}^{(1)} \mathbf{B} dA + \dots + t \int_{A_i} \mathbf{B}^T \mathbf{E}^{(i)} \mathbf{B} dA + \dots + t \int_{A_n} \mathbf{B}^T \mathbf{E}^{(n)} \mathbf{B} dA. \quad (5)$$

The displacement field of a medium in which two directions of variation of physical parameters occur, is approximated with shape functions whose form depends on the number of nodes adopted in an element (figure 3). In the four-node and eight-node spatial elements (figure 3a, c) polynomials are linear, and of the second degree in a plane eight-node element (figure 3b). Element stiffness matrices are determined by integrating functions of the internal energy in the subspaces marked by  $i$  according to the equation written in a general form:



**Figure 3:** Elements with layers in two and three directions: a) four-node element, b) eight-node plane element, c) eight-node spatial element

Modification of geometrical parameters of elements (dimensions, figure 3a), allows generating derivative internal structures with different geometries. It enables control of the numerical model being

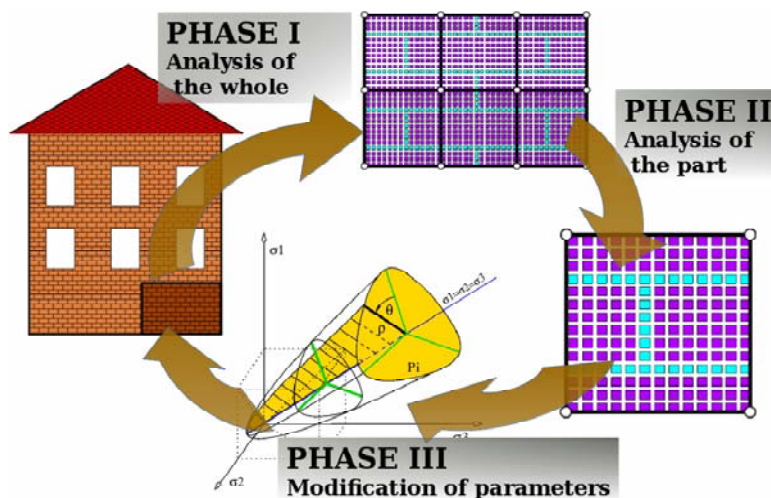
$$K_e = \int_{V_1} \mathbf{B}^T \mathbf{E}^{(1)} \mathbf{B} dV + \dots + \int_{V_i} \mathbf{B}^T \mathbf{E}^{(i)} \mathbf{B} dV + \dots + \int_{V_n} \mathbf{B}^T \mathbf{E}^{(n)} \mathbf{B} dV. \quad (6)$$

built in terms of coherence of adjacent structures of neighbouring elements and unification of the stiffness matrix calculation procedure.

In order to determine zones of material failure of complex structures as well as for identification of damage and parameters degradation, failure criteria are used [18]. To determine damage (failure) initiation in a modelled structure, it is proposed to use Rankine, Coulomb-Mohr and Christensen [19] criterion. The Coulomb-Mohr criterion is also applied for joints.

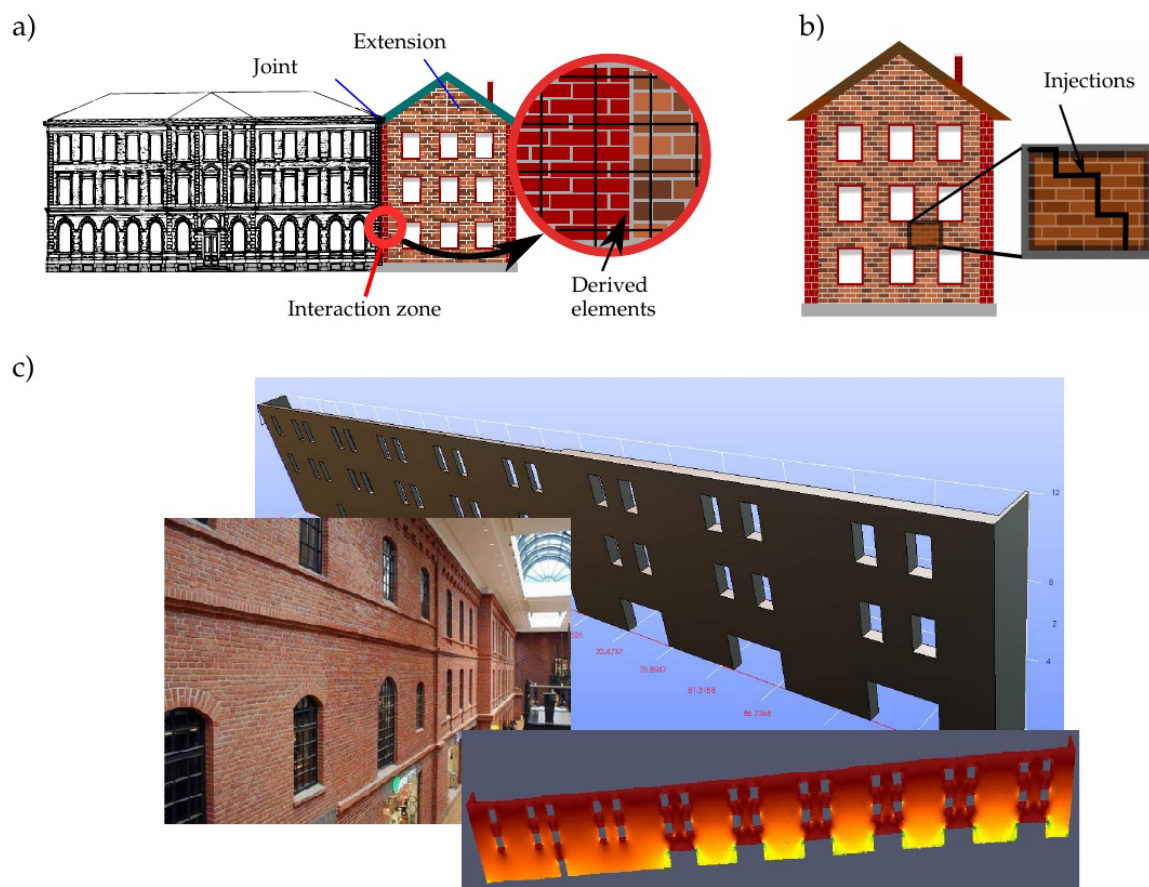
A computer simulation of the degradation process is proposed to be implemented according to the algorithm illustrated in the figure (figure 4). Propagation of a damage is determined by incremental-iterative procedure, using the secant stiffness matrix in each load step  $i$  and solving the equilibrium equations in the form:

$$K_i q_i = Q_i. \quad (7)$$



**Figure 4:** Strategy for performing numerical calculations





**Figure 5:** Applications: a) modernization and expansion, b) reconstruction and strengthening of masonry, c) analyses of large heterogeneous structures

#### 4. Summary and conclusions

Numerical simulations in addition to traditional methods of analysis are an alternative in the analysis of historical complex structures. Multi-criteria analysis provides information of the safety of elements and building structures. The proposed verification method of the effort state in complex structures makes the analysis of the phenomena caused by loads and degradation processes more accurate. The approach enables stress field determination and degradation modelling in materials and structures composed of heterogeneous materials. The practical application of the model are analyses of interaction zones including historical masonry buildings among others, their reconstructions and strengthening (figure 5). It makes possible to determine stresses in elements and structure before and after the reinforcement, in which traditional and modern materials and technologies have been applied. The advantage is a significant reduction of the number of finite element unknowns in a model. Proposed computer algorithm allows identification of degradation progress during renovation processes.

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