SAHC2014 – 9th International Conference on
Structural Analysis of Historical Constructions
F. Peña & M. Chávez (eds.)
Mexico City, Mexico, 14–17 October 2014

COMPUTATIONAL MODELING OF THE DETERIORATION OF HISTORIC MASONRY STRUCTURES

Simin Karimian, Dongmin Yang, Stephen W. Garrity and Vassili V. Toropov

School of Civil Engineering

University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK

E-mail: cen5s2k@leeds.ac.uk

Keywords: Historic masonry, Computational modelling, Deterioration, Climate change.

Abstract. *This paper describes a finite element-based computational tool that has been is developed to predict the structural behaviour of historic masonry, and to help the conservation industry find the best durable solution for maximising the protection of these structures.*

The model permits the end-user to investigate different rates of previous and predicted future material deterioration; changes in surface deterioration due to climate change, defects such as flooding, as well as variations in the surface temperature and moisture caused by weathering efflorescence, etc. In addition, a brief summary of concept of repair and most common repair methods on historic masonry structures is also given. This is then simulated to model and investigate the composite action between the original masonry and new repair materials such as grouts and mortars.

1 INTRODUCTION

Preservation of built heritage, in particular historic masonry, has high cultural importance to the construction industries and is one of their major concerns. Climate change is known to be one of the major factors affecting masonry structures [1]. Most forms of historic masonry are very complex composite materials that have been subjected to various physical, chemical and biological deterioration processes and actions over a prolonged period of time. The interaction between different forms of masonry construction in historic buildings further adds to this complexity. An increase in deterioration brings reduction of structural stability, increased risk of damage and in extreme cases, partial or complete collapse of the structure. In some cases, although large parts of the original structure can remain intact, the loss of robustness and support provided by the collapsed original walls and/or the roof structure makes the remaining parts particularly vulnerable to further disruption. Such vulnerability may be further heightened by the effects of climate change.

Those responsible for maintaining the safety and integrity of historic structures need to be able to assess the degree of risk of further damage or collapse and, where necessary, develop an appropriate strategy for rehabilitation, repair or strengthening. The inherent complexity of historic masonry structures usually requires the use of sophisticated analytical tools that can visualise the structure, capture its structural behaviour with sufficient accuracy to provide reliable guidance on the level of risk under a range of likely site conditions.

Development of a computational tool for the prediction of future behaviour of historic masonry structures subjected to climate change, as well as the effect of the repaired parts is essential for optimising the repair decision process. This will offer considerable benefits to the construction industry; particularly for maximising cost-effectiveness (materials and workmanship), time-management and leveraging value in the long term.

Existence of defects such as creep in historic masonry, is under a lot of attention in research, as it has proved to have significant influence on the behaviour of historical masonry structures [2, 3]. Creep occurs over a long period of time and can be defined as “the gradual increase in strain in masonry with time under a constant load” [4, 5]. As mentioned before, further emphasis and modelling of creep and crack is covered in second phase of this computational tool, in the following publications.

This research is divided into a two-pronged approach, the first of which is described fully in this paper.

The developed computational tool is based on the two-phased approach of:

1) Modelling the effect of deterioration of historic masonry, and
2) Modelling climate change defects such as creep and crack.

The first phase is discussed in this paper, and the second phase will be studied in a separate paper. As such, two models are presented in the following sections to illustrate:

a) Deterioration of masonry with time in the form of size reduction, due to climate change effects, and
b) The effects of reconstruction, repair and strengthening methods on deteriorated historic masonry structures.

Section 2 presents the computational modelling method used in this research to present the effects mentioned above. These models are then examined using the Finite Element Method (FEM) technique using ABAQUS (Dassault systems Simulia, version 6.13) and results are presented. Conclusions are then drawn from this work in Section 3.

2 COMPUTATIONAL MODELLING TECHNIQUE & RESULTS

2.1 Deterioration of masonry with time

The climate change consequences on structures, in particular historical structures, can be rooted back to a few parameters, namely temperature, moisture (in forms of rain, ice, snow and vapour clouds), soil conditions, radiation (in specific short-wave radiation) and wind. Presence of these parameters, cause consequences on historic masonry structures, such as weathering, salt crystallisation, efflorescence, frost, moisture, and so on.
Moisture is known as the most destructive one, as previous research and observations have revealed that most deterioration mechanisms trigger by the rainwater; rain may be described as a weak cocktail of acids that together with wind can fall and induce force on historical masonry and thus weaken its mortars [6]. Historic masonry, have high porosity and hence are at higher risks of deterioration. With the passage of time, the existing moisture in historic structures, can lead to mould growth at the interior surfaces of structure, increase in humidity of structure, creep in the masonry, appearance of crack, etc. [7-9].

One of the main defects of climate change can be named as exfoliation of masonry. It can be described as "peeling, swelling or scaling of masonry or mineral surfaces in thin layers". It is gradual deterioration of masonry, leading to reduction in the structure size with time. Crypto-florescence, salt-crystallization, freezing temperature, weathering and moisture result in swelling of outer layers and surface exfoliation:

a. *Crypto-florescence*
It is described as "a harmful mechanism whereby various soluble salts, crystallise in pores below the surface of the brick". In masonry structures, normally when brick dries out, the existing salts are pushed to the surface of the brick. However, a situation could arise where the water evaporates before the salts gets to the surface. This is when the salts turn into crystals by getting deposited into the brick pores, forming a dried zone in masonry. These salts cause expansion, and so, an internal pore pressure below the surface of the brick, at the interface of mortar bed joint and brick. The now-crystallised-salts spall the brick and in some cases result in removal of the whole brick surface; hence the term crypto-efflorescence [10-15].

b. Salt-crystallisation
In the long term, penetration of moisture and upward movement of damp eases the deposition of salt in pores of masonry - the rate of which increases with the change in temperature and humidity. Presence of hygroscopic salt available close to the outer surface can result in direct moisture absorption from the atmosphere. Changes in humidity and temperature can result in the salts going through cycles of solution and crystallisation; causing the dampness to persist and fretting of the masonry to continue [16]. Further crystallisation of salts, can lead to deterioration and exfoliation of masonry [14].

c. Weathering defects such as freeze-thaw
Continuous accumulation of moisture in historical masonry structures, especially in areas under severe natural-climatic conditions, usually results in regular freeze-thaw processes. As mentioned in the previous section, majority of historical masonry structures are subjected to frost deconstruction on the outer façade of the

buildings, due to poor-quality waterproofing of rubble foundation and penetration of moisture into the structure. In such structures, the missing rubble-concrete foundation and waterproofing leads to deformation defects such as moisture movement in the structures during warm periods and freeze of moisture during the cold periods of the year [17]. Cyclical appearance of freeze-thaw and propagation of crack in historical masonry structure and its foundation, results in reduction of their strength and makes them more vulnerable to structural defects such as frost, salt crystallisation and further cracks [18].

One of the examples of exfoliation of historical masonry structures is contour scaling, which can happen due to continuous contact of stone with airborne pollutants. As a result of contour scaling, brittle crust appears on outer surface of the stone. With constant change in climate, moisture is trapped underneath this crust. In extreme cold weather conditions, this moisture freezes, expands and causes spalling of the outer layer of the stone. With cyclic change in the climate, appearance of counter scaling repeats, which means that every time this takes place, new layers of stone spall.

A model is therefore developed to simulate size reduction in masonry structures as a result of deterioration over time; representing climate change defects.

Model Development

A good computational tool is one that is user driven, adoptable (to existing structures), customisable (in terms of material properties, loading and boundary conditions, etc.), dynamic and flexible. This is essential as in any structure; there exist various parts, conditions and material properties *etc*. that need to be modelled.

The use of FEM [19-24] and available commercial software packages such as ABAQUS offers great flexibility in modelling historic masonry structures. Application of user-specified sub-routines allows for high flexibility in terms of specifying material properties and mechanical behaviours (*e.g.* deterioration rate), as well as enabling parametric simulation of scenarios to examine the effects of various changes (e.g. climate change) in the structure under investigation.

The field variables of the model can be set so that the elements can be removed based on the stress or strain level. Details of how this can be used, can be found in [25], under section 'Deleting elements from an Abaqus/Explicit mesh using state variables'.

A dearth of experimental values for "deterioration rate" of masonry structures significantly limits the use of subroutines for this end. Therefore, a manual approach which affords a greater control and granularity must be adopted. This allows for the possibility of using a consistent rate of reduction in stiffness of historic masonry (details presented below), to remove the eroded material with time.

The main benefit of this model is that it gives the user a realistic estimate of existing defects in historic masonry structures and a plausible estimate of their remaining lifetime. The model becomes even more realistic when the combination of other climate change defects such as creep and crack are simulated, shown in the second phase. This will provide a more realistic understanding of the present state of the historic masonry structures.

Exfoliation of stone can therefore, be modelled as reduction in size of structure with time. A sample of such model has been carried out as follows. The model presented in Figure 1 is a simple block of historic masonry, which is fully encastered at one end with its upper surface under uniformly distributed pressure. It consists of three sets of different materials (shown as patches), given in Table 1, where materials 1, 2 and 3, represent ordinary, semi-eroded and eroded masonry materials, respectively.

To provide a framework example of the model, block of masonry (500x250x102 mm) consisting of three material types such as original masonry, an initial repair and a subsequent repair (properties of which are given in Table 1), is investigated. Total number of 2184 of hexahedral elements (type C3D8R) was used for meshing the block.

For each set of materials, the Young's modulus, *E*, reduces consistently with time, which depending on the situation in question, can have the units of days, months or even years; but needs to be consistent throughout the simulation. The patches of masonry that erode and peel off are modelled as a material whose stiffness is reduced over time; that is, eroded materials are given very low stiffness values (E = 50 N/mm^2) [26, 27]. The material set with the lowest stiffness is given a material property similar to foam; resembling a patch with physical existence but no ability to carry the distributed load. This would, therefore, put more pressure on other patches which in turn increases the chance of failure.

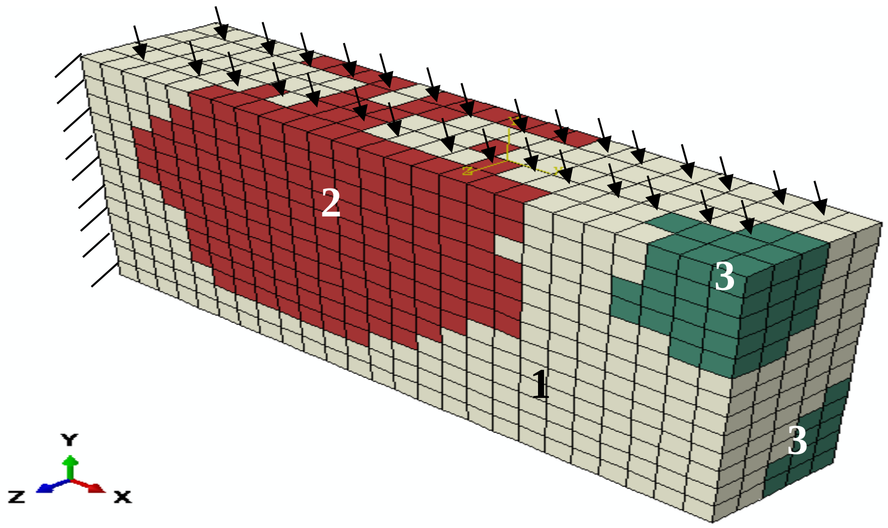

Figure 1: Example of different sets of materials; (1) Ordinary masonry, (2) Semi-eroded masonry, (3) Eroded masonry.

As is evident from Figure 2, the eroded material (set 3) reaches a low stiffness after 10 years indicating a potential exfoliation and so, the geometry of set 3 is removed to represent part of the block that has been most exposed to weathering. This is then followed by removal of semi-eroded material (set 2), after 20 years (Figure 3). With removal of each batch of material, the stability of the stress/strain distribution across the block is disturbed. Removal of eroded material, helps the user visualise this effect better.

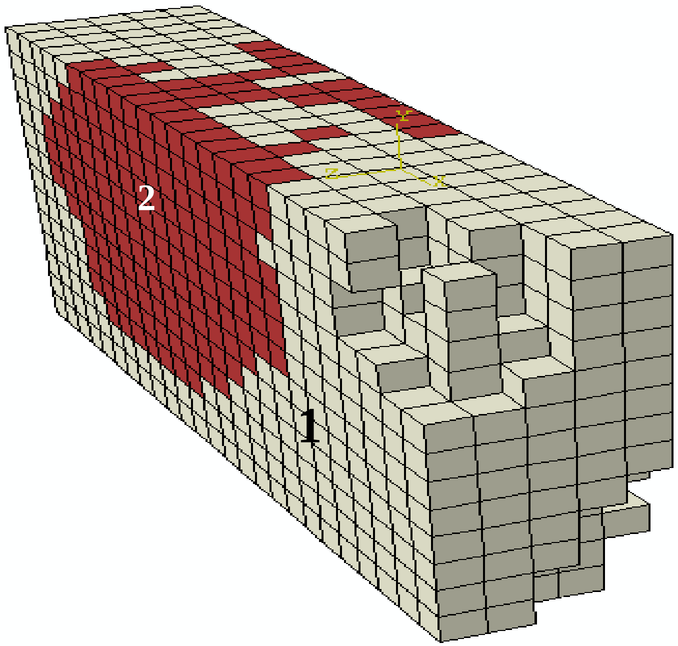

Figure 2: After removal of the eroded material.

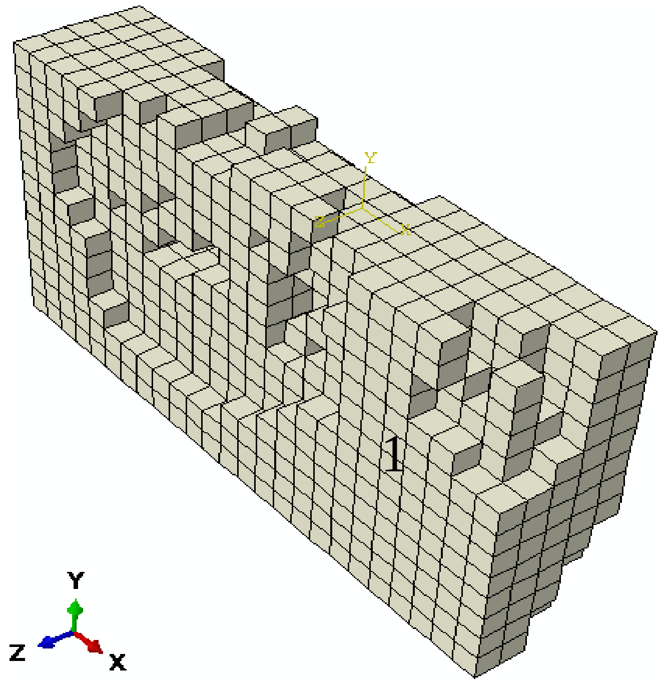

Figure 3: After removal of both semi-eroded materials.

Table 1: Material properties of different sets, indicating reduction in stiffness with time.

Ordinary masonry (Set 1)		Semi-eroded material (Set 2)		Eroded Material (Set 3)	
E (N/mm^2)	*Time (years)*	*E (N/mm^2)*	*Time (years)*	*E (N/mm^2)*	*Time (years)*
6000	1	4000	1	2000	1
5800	2	3750	2	1750	2
5600	3	3500	3	1500	3
5400	4	3250	4	1250	4
5200	5	3000	5	1000	5
5000	6	2750	6	750	6
4800	7	2500	7	500	7
4600	8	2250	8	250	8
4400	9	2000	9	150	9
4200	10	1750	10	50	10
4000	11	1500	11		
3800	12	1250	12		
3600	13	1000	13		
3400	14	750	14		
3200	15	500	15		
3000	16	400	16		
2800	17	300	17		
2600	18	200	18		
2400	19	100	19		
2200	20	50	20		
2000	21				
1800	22				
1600	23				
1400	24				
1200	25				
1000	26				
800	27				
600	28				
400	29				
200	30				

Repaired material (Set 1)	
E (N/mm^2)	*Time (years)*
7000	11
6800	12
6600	13
6400	14
6200	15
6000	16
5800	17
5600	18
5400	19
5200	10

2.2 Effect of repair on deteriorated masonry

The main philosophy of conservation engineering (established in Europe in 1980s), is minimum intervention to the structure, which means that while deciding the appropriate approach for conservation of monuments, the original material should be respected and priority should be given to the approach which involves the least alteration, modification or removal of the original material [28]. The Venice Charter, states that “Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence” [29].

Historic masonry features can be repaired through [28]:

- Replacing the deteriorated or missing parts
- Preventing water penetration
- Repairing materials due to creep
- Repairing and testing of the cracked sections
- Grouting injection
- Patching
- Reinforcing (using recognised preservation methods)
- Confinement

It is noted that inappropriate repair leads to further damage of historic masonry structures, with the main causes being lack of knowledge of the constitutive material, as well as inadequate workmanship skills [34]. An example of further damage is evident in Figure 4, after applying new mortar on outer façade of the Liverpool Anglican Cathedral.

Figure 4: Inappropriate repair on outer surface of the Liverpool Anglican Cathedral has caused further crack and damage.

As it is known, repairing the eroded areas most often involves introducing new materials (with higher stiffness, E) to that area of the structure. Use of repair in form of incompatible patches in this paper shows that the application of such repair on any part of the structure can change the overall stress/strain distribution and could have adverse effects on the stability of the structure. Therefore, the computational tool used in this paper proves to be very useful in modelling the application of suggested repairs on historic masonry structures, as well as analysis of the effects of these repairs (based on existing defects). Depending on the results of such analysis, material properties of the patch can either be altered to better fit the existing structure; or alternatively, application of other repair techniques can be considered.

In the proposed model, the repaired material has been applied to the masonry block presented in Section 2.1. After removal of the eroded material, Set 3, the repaired material is applied to this set; details of which are shown in Table 1. The effect of repaired materials on the existing materials (Sets 1 and 2) has been simulated for duration of 10 years (from 11 to 20 years).

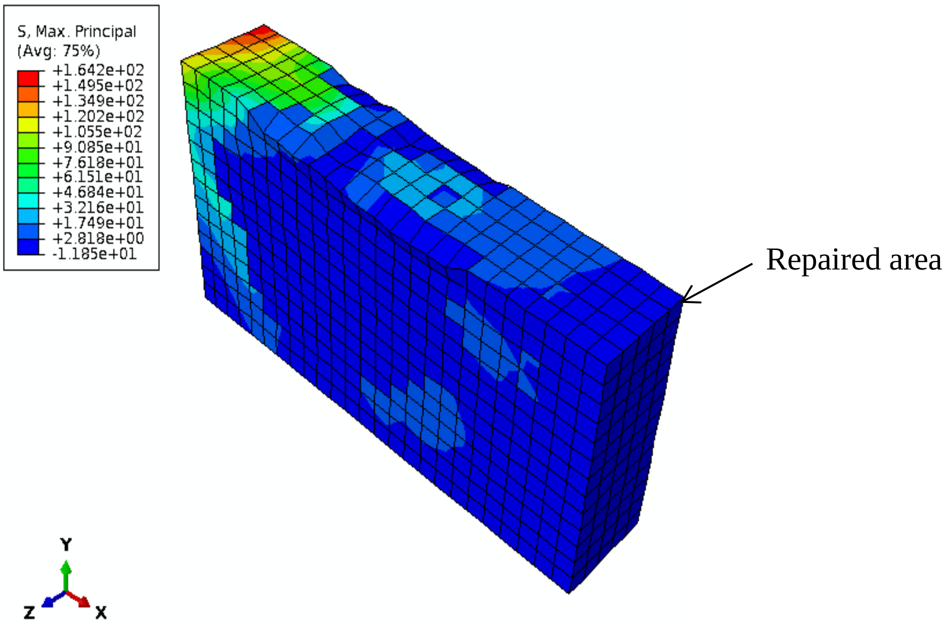

Figure 5 Maximum principal stress of the block, after application of repair to eroded areas.

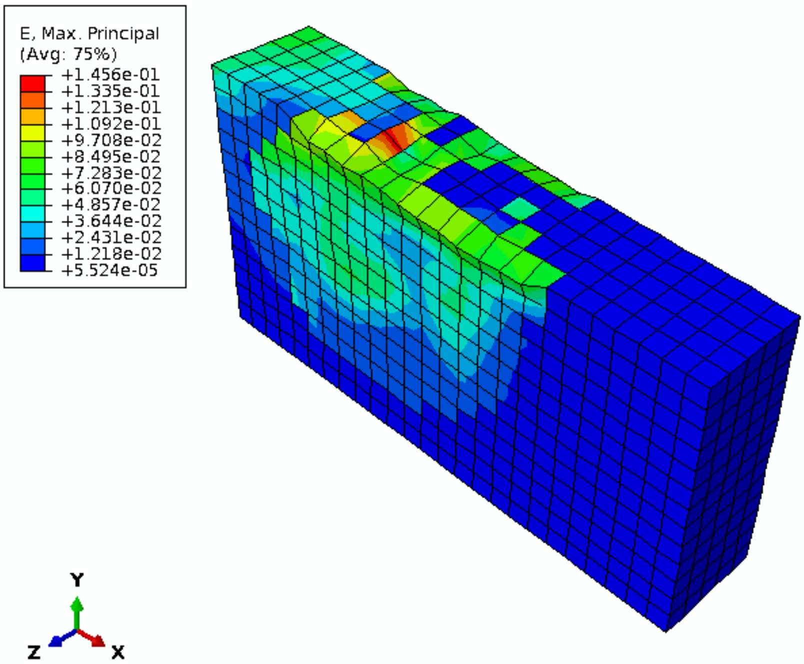

Figure 6 Maximum principal strain of the block, after application of repair to eroded areas.

Figures 5 and 6 represent the maximum principal stress and maximum principal strain contours, respectively. It can be seen that with application of load, the repaired part has much lower deformation, in comparison with the semi-eroded set. The section between the semi-eroded material and ordinary masonry face the highest level of deformation.
In Figure 5, maximum and minimum stress levels are shown in colours red (areas in tension) and blue (areas in compression). The fixed end of the block is bearing the highest level of stress, when the least level of stress is shown in the repaired section. The areas surrounding the repaired section are also bearing relatively low stress, as the strength of the new material has helped with a better stress distribution in the block.
Similar pattern of strain can be seen in Figure 6. The highest and lowest levels of strain are shown in colours red and blue, respectively. The repaired areas are least strained, whereas the semi-eroded areas and the section between the semi-eroded area and ordinary masonry have the highest levels of strain. It is evident that the semi-eroded materials also need repair.
In such cases, various repair method (with different stiffness values) can be applied to the structure and the best type of repair can be chosen by comparing their effect on stress/strain distribution of the masonry block.

3 CONCLUSION AND FUTURE WORK

This paper presented the results of the first phase of a computational modelling approach that has been proposed to simulate deterioration and erosion of a simple historic masonry block, to test the idea of reduction in stiffness with time and removal of the eroded sections. This helps give an insight into surface erosion.

In order to examine the effect of repair on stress distribution of the structure a new material set was added to the model to replace the eroded area, representing the repair of historic masonry,

The paper illustrates the importance of considering and applying the proposed computational tool to historic masonry structure to obtain better visualisation of the realistic behaviour of such structures, as well as predicting their behaviour over time; whereby illustrating its potential usage on a wider scale.

REFERENCES

[1] J.V. Lemos, *Modeling stone masonry dynamics with 3DEC*. Taylor & Francis, 2004.

[2] A. Anzani, L. Binda, G. M. Roberti, *The effect of heavy persistent actions into the behaviour of ancient masonry*. Materials and Structures, 33, 251-261, 2000.

[3] A. Anzani, L. Binda, G.M. Roberti, *Time dependent behaviour of masonry: Experimental results and numerical analysis*. 415-422, 1993.

[4] A. Bremner, *The Origins And Effects Of Cryptoflorescence In Fired-Clay Masonry*. School of Civil Engineering. Leeds, University of Leeds, 2002.

[5] A. Tomor, E. Verstrynge, A joint fatigue - creep deterioration model for masonry with acoustic emission based damage assessment. *Construction and Building Materials*, 43, 575-588, 2013

[6] J. Ashurst, *Conservation of ruins, Routledge*. 2012.

[7] P.R. Bingel, *Stress relaxation creep and strain under varying stress in masonry*, in *School of Civil Engineering.* PhD thesis, University of Leeds, 1993

[8] T. Kvande, K.R. Lisø, Climate adapted design of masonry structures. *Building and Environment*, Vol. 44, P 2442-2450, 2009.

[9] M. Abuku, H. Janssen, S. Roels, *Impact of wind-driven rain on historic brick wall buildings in a moderately cold and humid climate: Numerical analyses of mould growth risk, indoor climate and energy consumption.* Energy & Buildings, 41, 101-110, 2009.

[10] J. P. Forth, J.J. Brooks, Cryptoflorescence and its role in the moisture expansion of clay brick masonry. *Masonry International*, 14, 55-60, 2000.

[11] J. M. Hardesty, *Disintegration of face brick by dissolved salts*. Bell Laboratories Record, 22, 222-224,1944.

[12] B. Butterworth, The florescence test and the chemical examination of florescences. *Trans. Brit. Ceram. Soc.*, Vol. 36, 270-283, 1933.

[13] I. R. Chin, L. Petry, *Design and testing to reduce efflorescence potential in new brick masonry walls*. Masonry: design and construction, problems and repair, 1993.

[14] A. Bremner, *The Origins And Effects Of Cryptoflorescence In Fired-Clay Masonry*. School of Civil Engineering. Leeds, University of Leeds, 2002.

[15] H. W. Harrison, R. C. de Vekey, *Walls windows and doors*. BRE Building Elements series, 1998.

[16] E. M. Leif, R.Heinz, *Moisture migration in building: a symposiu, Philadelphia, Pa.*,ASTM special technical publication/ American society for Testing and Materials 779, 1982.

[17] V. P. Vlasov, Causes of deformations and crack formation in an administrative building in Magadan. *Soil Mechanics and Foundation Engineering*, 46, 158-162, 2009.

[18] A.H. Rahman, G.T. Suter, An analytical study of extreme temperatures in masonry building walls. *Masonry International*, 6(3): p. 89-95, 1993

[19] G.R. Liu, S. Quek, *The Finite Element Method: A practical course*. Butterworth-Heinemann, 2003

[20] K.H. Huebner, D.L. Dewhirst, D.E. Smith, T.G. Byrom, *The finite element method for engineers*. John Wiley & Sons, 2008

[21] J.C. Heinrich, D.W. Pepper, *Intermediate finite element method: fluid flow and heat transfer applications.* Taylor & Francis, 1999

[22] M.A.N. Hendriks, J.Rots, *Finite Elements in civil engineering applications*. in *DIANA Foundation*, Tokyo, 2002

[23] D. Chapelle, K.J. Bathe, *The Finite Element Analysis of shells: Fundamentals.* Springer Verlag, 2003.

[24] J. Fish, T. Belytschko, *A first course in Finite Elements*. Wiley Online Library, 2007

[25] Dassault Systèmes Simulia Corp., ABAQUS Analysis User Manual, Section 25.7.1, Version 6.11, *http://50.16.176.52/v6.11/books/usb/default.php*, Date accessed 08.4.2014

[26] B. Kralj, J. Middleton, G.N. Pande, Numerical model for the prediction of frost damage to brickwork. *Masonry International*, 4(3): p. 89-93, 1991

[27] B. Gigla, F. Schlesinger, Investigatin into the sustainability of industrial fixing systems for the repair of historic masonry. *14th International Brick and Block Masonry Conference*, Sydney, 2008

[28] E. Verstrynge, *Long-term behaviour of monumetal masonry constructions: modelling and probabilistic evaluation.* Leuven University, Belgium: Katholieke Universiteit Leuven, 2010

[29] K.D. Weeks, A.E. Grimmer, *The Secretary of the Interior's Standards for the Treatment of Historic Properties: With Guidelines for Preserving, Rehabilitation, Restoring & Reconstructing Historic Buildings*. Washington, DC: US Dept. of the Interior, Natioanl Park Service, 1995