ENERGY AND MECHANICAL PERFORMANCES OF AN EXTERNAL BUILDING CLADDING

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ABSTRACT

In the present paper, thermal performance of a cladding on the outer surface of a building wall was investigated by a simulation in transient conditions using a Computational Fluid Dynamics tool (CFD), with Finite Element Method (FEM).

A typical external insulation building cladding consisting of a layer of insulation and a multi-layer reinforced coating system, was considered placed on the external light clay brick wall. The transient simulation was performed by taking into account hourly climatic data of Florence (Italy) for summer. Structural simulation results, obtained using ANSYS, provided the thermo-mechanical behaviour of the cladding related to fatigue stresses and fatigue crack process.

The obtained transient simulation results, given that the outside location of the external cladding provides low amplitude of load fluctuation and summer peak loads for all the orientations of building walls assuring stable indoor thermal conditions and comfort. As an efficient alternative, this paper presents an analysis of the force transferred to cladding fixtures when the panel is subjected to impulsive loading and changing thermal loads.

Comparison with the simulated thermal performance of the wall without the insulation system showed that external insulation is particularly effective in reducing cooling and heating loads, considering the same indoor thermal conditions.

INTRODUCTION

The insulation efficiency of building exterior walls can be the single most important area in which energy saving can be achieved. Energy performances of buildings can be improved by a proper insulation envelope. Many studies have been carried out on this subject to investigate the effectiveness of better thermal insulation for existing buildings to reduce energy consumption [1,2,3,4,5]. Better insulation levels imply energy benefits connected to lower environmental impact due to lower energy use for heating and cooling with the plant system considered, but at the same time some critical economic issues. In a recent paper it was shown that the environmental extra loads (energy, environment, economy) due to greater use of building insulation can be recovered in a few years with important social and ambient benefits, especially if the life cycle of the building-plant system is taken into account, including higher initial costs and environmental loads due to production of better insulating materials [6,7,8,9].

Adding or retrofitting insulation to existing buildings provides an opportunity to increase thermal comfort, indoor air quality and also reduce energy cost and greenhouse gas emissions caused by electricity and fuel consumption. Building heating and cooling loads basically depend on thermal transmittance of the envelope components, but this dependence is not linear and it has been demonstrated that over a certain thickness is not effective [5]. Optimal insulation thickness also depends on climatic conditions, building geometry and location. It is well known that 40% of energy end uses concern the building sector in Europe and 70% existing residential buildings [2,6,3]. Several studies have shown the poor energy performances of Italian buildings, particularly when normalized to climatic conditions according to the different Heating Degree Days (HDD) [4]. Better insulation systems of the opaque building components can be useful for heating but also for the cooling season, improving the overall building energy performances. The outer walls of the building interact with solar radiation and air temperature variations and this causes continuous surface temperature and heat flux transfer variations over time that are connected to cyclic fatigue stress of the different materials. In the present paper thermal and mechanical performances of building cladding on the outside surface of a traditional wall were investigated by a simulation in transient conditions during the summer period.

THE SIMULATION

A type of commercial insulation usually known as exterior insulation and finish systems (EIFS) on the external walls of new and existing buildings was taken into account (Fig.1). A number of factors contribute to analysing this insulation system and foregrounding its energy performance i.e. its exterior location, the effectiveness of a continuous unbroken layer of insulation, its total high thermal resistance value and the lack of thermal bridges through the insulation layer. This insulation system is usually attached to the wall with adhesives or mechanical anchors. The insulation is in the form of preformed sheets of foam plastic, such as expanded polystyrene and similar materials. The reinforced coating system can consist of an adhesive into which is embedded a glass reinforcing mesh and attractive, coloured, textured, finish coating. It resembles Portland cement plaster and concrete, but can also be made to imitate many other common materials and architectural styles such as stone. It is usually installed on the construction site by plasterers but can also be made in the factory in the form of panels. The panels have a metal sub-frame and are ready to install wall units. Panels are then transported to the site, lifted into place and attached to the building frame. It thus allows realisation of large monolithic wall areas. It eliminates places where water and air can get through the cladding, thus improving thermal efficiency and weather resistance. A typical external insulation building cladding that consists of a layer of insulation and a multi-layer reinforced coating system was studied. Thermal and mechanical properties of the different materials of the system studied, according to the standards [10,11], are shown in Tab.1. The three dimensional model of the studied system was produced by importing its geometry and architectural properties from a CAD data base. The simulation in transient conditions was realized on the system placed on an external light clay brick wall, using a computational fluid dynamics software based on the finite element method [12]. For natural convection analysis the software uses the classical hypothesis based on Boussinesq approximations [13,14]; for radiative flux evaluation, from surface to the ambient, the software uses radiosity balance and then for the external opaque surface a uniform value of the solar emissivity i.e. 0.2, and of the emissivity in the infrared field, i.e. 0.9, was assumed.

Transient simulation required the following: assembly utilization for the 3D drawing of the geometry; mesh generation with quadratic order elements utilisation; computational domain and sub-domain definition and setting; thermo-physical properties assignment to the different materials; boundary conditions definition; solving for heat transfer analysis (convective, radiative and conductive). The meshing technique used for the 3D model provided a “finer” mesh with 12334 degrees of freedom and a total 60820 tetrahedral elements. The transient simulation was performed by taking into account hourly climatic data for summer in Florence (Italy) and southern and south-western orientation.

The outdoor air temperatures and total incident solar radiation were obtained for the hottest summer day in Florence from the corresponding hourly measurements recorded in meteorological data of the Standard Year [15]. Table 2 shows the external climatic parameters used. The boundary conditions used for general heat transfer transient computation are linked to the outside hourly air temperature values and heat exchange coefficients for the external surface of the insulation cladding; the same boundary conditions for the internal surface of the wall. For convection analysis the general boundary condition was the “no-slip” for both the external insulation system and the standard wall. Transient simulation was performed for 31 July both for southern and south-western orientation of the system studied [15]. The initial conditions for this transient computation were obtained by running the simulation for some days before, assuming for the initial indoor climatic conditions a uniform internal air temperature of 24 °C, as usually suggested for indoor summer comfort [16,17]. The simulation was performed on a summer day because the external summer climatic conditions are usually more critical for the structure of the insulation system, and bring higher cooling loads for the inside ambient due to high incident solar fluxes in the presence of higher air temperature values than in winter. This is a common situation at medium latitudes such as of Florence.

The structural analysis of a 3D model of a building façade with external cladding was performed using ANSYS. Hourly temperature distribution of different material strata, obtained by the thermal transient simulation, was used as a boundary condition. Simulations were carried out considering the cladding with fixed joint constraints.

RESULTS AND DISCUSSION

Because heat losses and gains vary with the inverse of thermal resistance, successive increase in the thickness of insulation should be controlled with particular attention to location and local climate. Simulation results obtained show that external insulation cladding is particularly effective in reducing cooling loads at average low latitudes (40°-45°), where the amount of summer total solar radiation striking the building walls is very important. This causes the temperature of the external surface of insulation to be greater than the air temperature, so that the effect of external insulation in reducing the cooling load is higher than expected when evaluated by difference between indoor and outdoor air temperatures.

Figure 2 provides the temperature profiles for the southern orientation comparing the surfaces temperature trend of the wall with and without cladding . Table 3 shows thermal properties of the materials used for the wall without insulation.

The temperature profile trend of the inside surface of the wall is the same as the one with external insulation cladding, but with higher values. As a consequence of this, the hourly values of the total heat flux coming into the internal ambient are lower for the walls with external cladding (Figures 3 and 4): e.g. for 2 p.m., when the total incident solar radiation is 747 W/m^2 with an incidence angle of 54° and the correspondent air temperature is 35 °C, the total heat flux entering the studied building system is 1.39 W for the wall with external insulation cladding, and 16.86 W for the wall without insulation. This result is also supported by the thermal resistance value calculated for the wall with and without external insulation: the corresponding value for the two configurations is respectively 3.34 m^2 K/W for the wall with external insulation, and 1.42 m^2 K/W for the wall without. The worst orientation for the Florence latitude is South-West, referring to summer cooling of buildings, then transient simulation was performed for the external cladding 3D model with a south-western orientation. In this case the external cladding temperature trend is close to those of south orientation but with higher values (fig.5): e.g. at 2 p.m. the external cladding temperature is 70 °C and 57 °C, respectively for the south-western and south orientation, when at the same time the outside surface temperature of the brick wall is 33 °C and 38 °C; in particular at this hour the total incidence solar radiation for the south-western orientation is 1096 W/m^2 with an incidence angle of 38°.

The analysis of structural simulation provides the thermo-mechanical behaviour of the cladding related to fatigue stresses and fatigue crack process. The simulation was related to an entire 3 x 4 meters wall. Figures 6 shows the fatigue stresses along x direction: the range of the stress values is connected to the compressed state of the structure due to the fixed joint constraints. The external covering of the cladding shows the higher values and in particular in the zone of the anchors (absolutely rigid): the stress range value is $7.5\ 10^6$ – $8.8\ 10^6$ N/m^2. This value is lower than the maximum admittable limit for the external plastering. The overall stress conditions of the cladding are uniform and quite low due to the low material rigidity. A second simulation was performed considering the cladding without vertical edge constraints on one side, so that the insulating material and the external plastering can move along the x direction (Fig.7). Figure 8 shows a bending stress of the covering panel due to rotation of the polystyrene stratum fixed to the inside wall frame.

Simulation results provide this same problem for the external plastering of the cladding (Fig. 8). A traction state with values between $0.2\ 10^6$ and $0.87\ 10^6\ N/m^2$, is present on the plastering external surface particularly important taking into account the low pull strength resistance of the covering material.

CONCLUSIONS

The transient simulation results show that the outside location of insulation provides low amplitude of load fluctuation and summer peak loads for all the orientations of building walls assuring stable indoor thermal conditions and comfort. The benefit of external cladding, for an existing building location in a moderately hot climate (1821 HDD) is shown. The worst orientation was taken into account for thermal performance comparisons of the insulation cladding.
Structural simulation analysis shows the higher temperature differences cause allowable tensional stresses on the external cladding with fixed joint constraints. Critic conditions can be due to free to move edge connections. As a matter of fact, areas of the covering system, with important pull strengths, that can produce fatigue crack, appear near the free edges (Fig. 7). In accordance with most of the literature on the optimal thickness and location of building insulation [6,3,18], the conclusions of the present paper are a fundamental support for investigation on the overall thermal performances of external insulation for the best building cooling but also heating load reduction. In particular, transient simulation results include energy performance of the external insulation in terms of thermal inertia and solar gains of the different components.

The results obtained might be used to address building sector operators in development new design solutions for a climate with high summer temperatures and solar radiation fluctuations. This action would be very important to promote Italian building stock renovation according to the requirements of European Directive 2002/91.

REFERENCES

[1] Arslan O., Kose R. Thermoeconomic optimization of insulation thickness considering condensed vapour in buildings. Energy and Buildings 38 (2006) 1400-1408.

[2] Balaras C.A., Droutsa K., Dascalaki E., Kontoyannidis S. Heating energy consumption and resulting environmental impact of European apartment buildings. Energy and Buildings 37 (2005) 429-442.

[3] Comakli K., Yuksel B. Optimum insulation thickness of external walls for energy saving. Applied Thermal Engineering 23 (2003) 473-479.

[4] Lollini, Barozzi, Fasano, Meroni, Zinzi. Optimisation of opaque components of the building envelope. Energy, economic and environmental issues. Building and Environment 41 (2006) 1001-1013.

[5] Mahlia T.M.I., Taufiq B.N., Ismail, Masjuki H.H. Correlation between thermal conductivity and the thickness of selected insulation materials for building wall. Energy and Building 39 (2007) 182-187.

[6] Brandt E., Rasmussen M.H. Assessment of building conditions. Energy and Buildings 34 (2002) 121-125.

[7] Danny Harvey L.D. Net climatic impact of solid foam insulation produced with halocarbon and non-halocarbon blowing agents. Building and Environment 42 (2007) 2860-2879.

[8] Ozkahraman H.T., Bolatturk A. The use of tuff stone cladding in buildings for energy conservation. Construction and Building Materials 20 (2006) 435-440.

[9] Swinton M.C., Maref W., Bomberg M.T., Kumaran M.K., Normandin N. In situ performance evaluation of spray polyurethane foam in the exterior insulation basement system (EIBS). Building and Environment 41 (2006) 1872-1880.

[10] UNI 10351. Materiali da costruzione. Conduttività termica e permeabilità al vapore. 1994. Italian Standard.

[11] UNI 10355. Murature e solai. Valori della resistenza termica e metodo di calcolo. 1994. Italian Standard.

[12] COMSOL. MULTIPHYSICS 3.3a. COMSOL Reaction Engineering Lab, COMSOL (comsol.com)

[13] Kreith F. Principles of Heat Transfer. South West College Pub. 1996. London.

[14] Mills A.F. Basic Heat and Mass Transfer. Prentice Hall Ed. 1999. London.

[15] Alabisio M., Sidri R. Gestione archivio Anno Tipo. ENEL CRTN 1985, Milano.

[16] D.Lgs.n. 192/2005. Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia. pubblicato nella Gazzetta Ufficiale n. 222 del 23 settembre 2005 - Supplemento Ordinario n. 158.

[17] D.lgs.n.311/2006. Disposizioni correttive ed integrative al Decreto Legislativo 192/2005. Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia.

[18] Ozel M., Pihtili K. Investigation of the most suitable location of insulation applying on building roof from maximum load levelling point of view. Building and Environment 42 (2007) 2360-2368.

Nomenclature

E elasticity coefficient ($N\ m^{-2}$)
I total incident solar radiation ($W\ m^{-2}$)
s thickness (m)
t air temperature (°C)
w wind velocity ($m\ s^{-1}$)

Greek letters

α thermal expansion coefficient (K^{-1})
λ thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ density ($kg\ m^{-3}$)
σ admittable tension ($N\ m^{-2}$)

Subscript

e external
max maximum
South southern orientation

Table 1. Hourly climatic data – 31 July, Florence

hour	t_e (°C)	I_{South} (Wm^{-2})	$I_{South-West}$ (Wm^{-2})
1	20.2	0	0
2	19.1	0	0
3	18.1	0	0
4	17.4	0	0
5	17.2	13	11
6	17.3	128	89
7	17.8	303	182
8	19.9	479	281
9	23	629	375
10	27	747	454
11	29.5	821	634
12	31.7	845	875
13	33.6	822	1035
14	35	747	1096
15	36	629	1054
16	36.6	479	922
17	36	303	726
18	34.5	125	499
19	32.2	13	272
20	30.2	0	0
21	27.9	0	0
22	25.4	0	0
23	23.1	0	0
24	20.9	0	0

Table 2. Thermo-physical and mechanical properties of the materials making up the wall with external cladding

Layers	s (m)	ρ ($kg\ m^{-3}$)	λ ($Wm^{-1}K^{-1}$)	E ($N\ m^{-2}$)	α 10^{-6} (K^{-1})	σ_{max} 10^6 ($N\ m^{-2}$)
Internal plastering	0.015	1400	0.7	$2\ 10^9$	25	12.8
Light clay brick	0.20	1400	0.5	$20\ 10^9$	6	63
Expanded polystyrene	0.08	20	0.04	$5\ 10^6$	80	0.17
External plastering	0.02	1400	0.7	$2.9\ 10^9$	25	12.8
Mortar	0.005	1000	0.8			

Tab. 3. Thermo-physical properties of the materials making up the wall without external cladding

Layers	s (m)	ρ ($kg\ m^{-3}$)	λ ($W\ m^{-1}\ K^{-1}$)
Internal plastering	0.015	1400	0.7
Light clay brick	0.20	1400	0.5
External plastering	0.02	1400	0.7
Mortar	0.005	1000	0.8

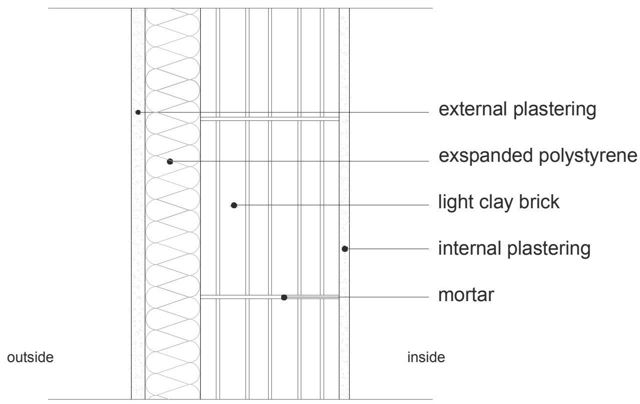


Fig.1 Schematic section of the wall studied with external cladding.

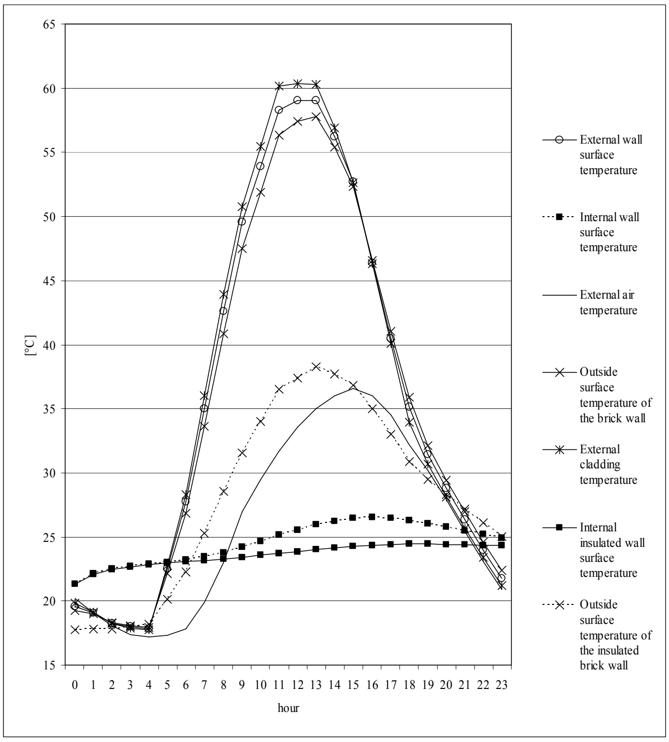


Fig.2 Hourly temperature value trend for the wall with and without external cladding; 31 July, South.

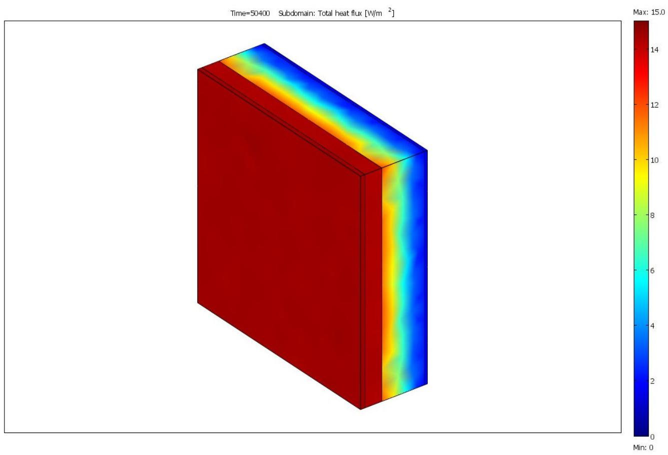


Fig.3 Total heat flux through the wall with external cladding (the latter on left-side of the image); 31 July, South, 2 p.m.

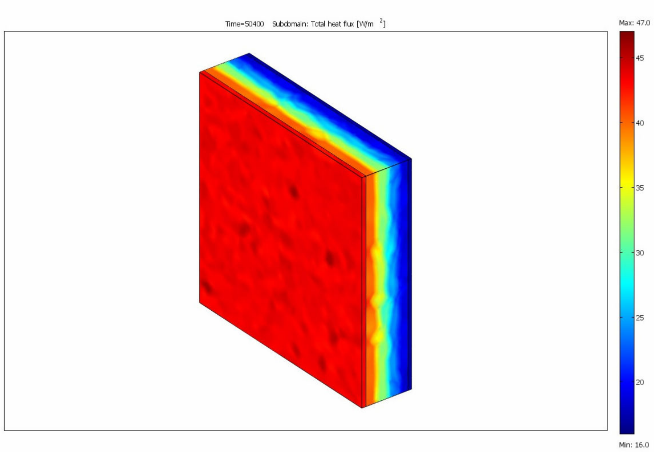


Fig.4. Total heat flux through the wall without external cladding; 31 July, South 2 p.m.

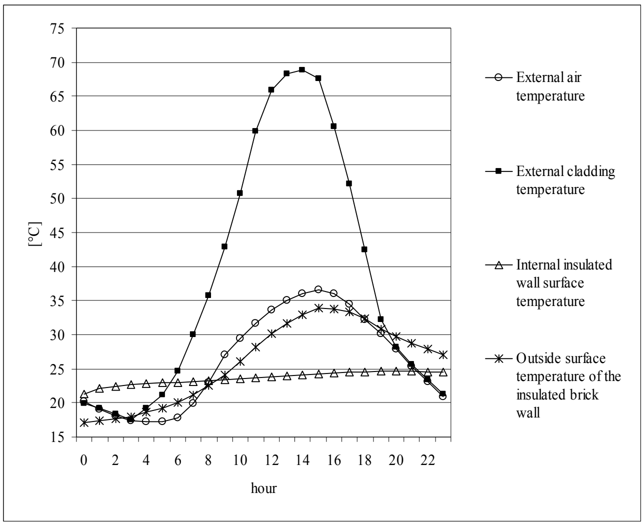


Fig.5 Hourly temperature value trend for the wall with external cladding; 31 July, South-West.

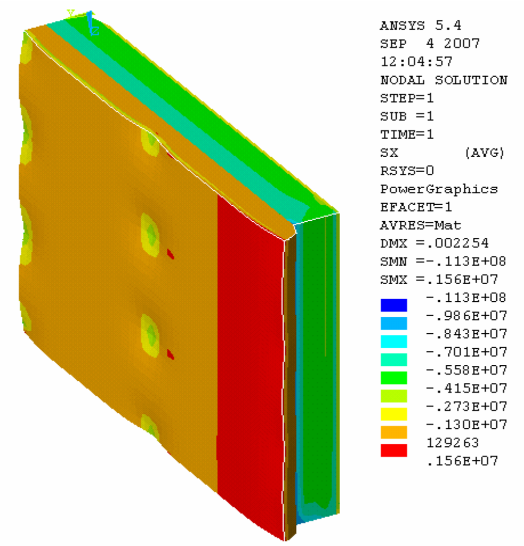
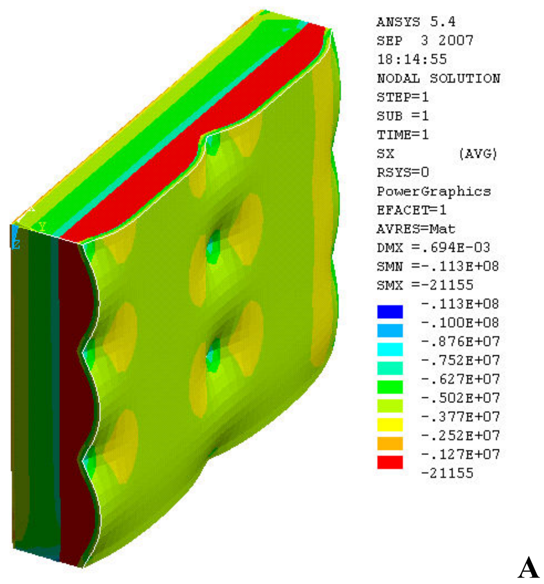


Fig. 7 Fatigue stresses along x axes; model without fixed joint constraints.



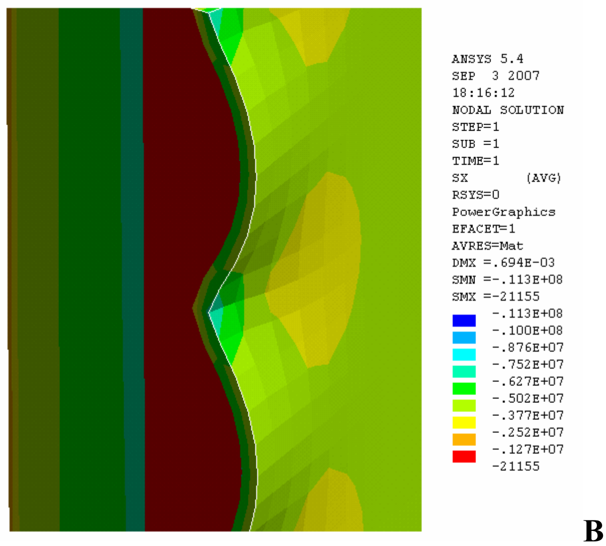


Fig. 6 **A**: Fatigue stresses along x axes – model with fixed joint constraints; **B**: detail

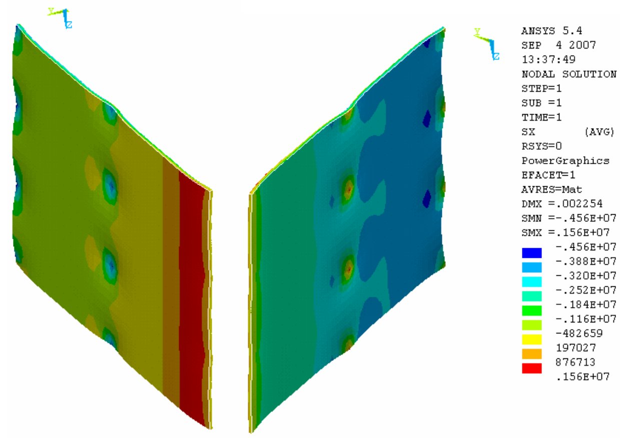


Fig. 8 Fatigue stresses along x axes – model without fixed joint constraints – detail of the external covering with outside and inside views.