The External Thermal Insulation Composite System (ETICS) More than comfort and energy saving

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Abstract: The External Thermal Insulation Composite System (ETICS) is the only viable solution for the energetic upgrading of the existing buildings.
However the effects of the ETICS installation are not limited to the energy saving and comfort, but include the protection of the building structure from the stresses caused by temperature differences. The stress is transferred into the ETICS System, in particular into the adhesive which links the insulation panel to the render of the external masonry.
A detailed analysis of the peel and shear stress condition of the adhesive, generated by the restrained differential thermal elongations of the insulation panel, is presented.

Keywords: ETICS, Thermal insulation, Adhesive, Shear stress, Peel stress.

1. INTRODUCTION

The energetic performance of a building, which has been considered not significant in the past, is becoming more and more important because of the environmental constraints and the increasing cost of the fuel.
The external thermal insulation composite system (ETICS) is the only viable solution for the energetic upgrading of the existing buildings.
However, the effects of the installation of the external thermal insulation composite system are not limited to the energy saving; a number of advantages are really obtained as indicated hereunder.

2. ETICS DESCRIPTION

ETICS is a system usually including an adhesive, a leveling mortar, an insulation panel, an alkali-resistant reinforcement grid, a primer and a finishing coat, as well as sealants and accessory materials for the installation [1]. (Figure 1)

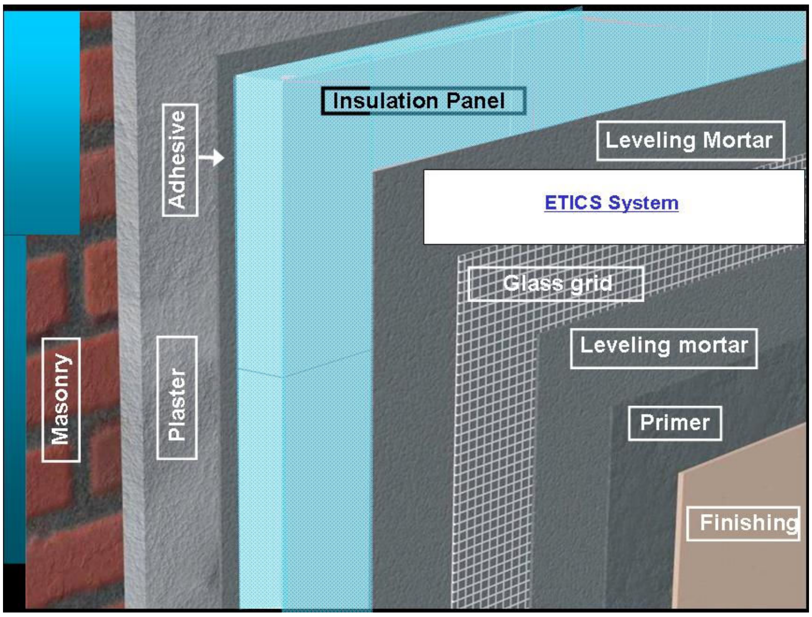


Figure 1: ETICS stratigraphy

Being ETICS a multi-component system, the compatibility among the components is a key factor in order to obtain the performances of the overall system as well as its durability

3. REFERENCE WALL STRATIGRAPHY

The reference wall considered in the present work is reported in Figure 2.

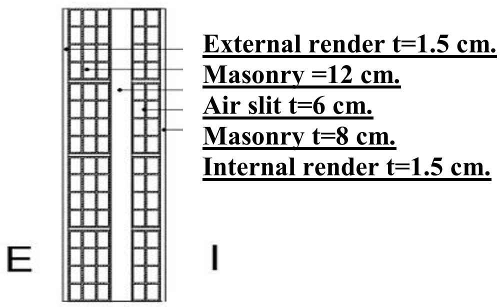
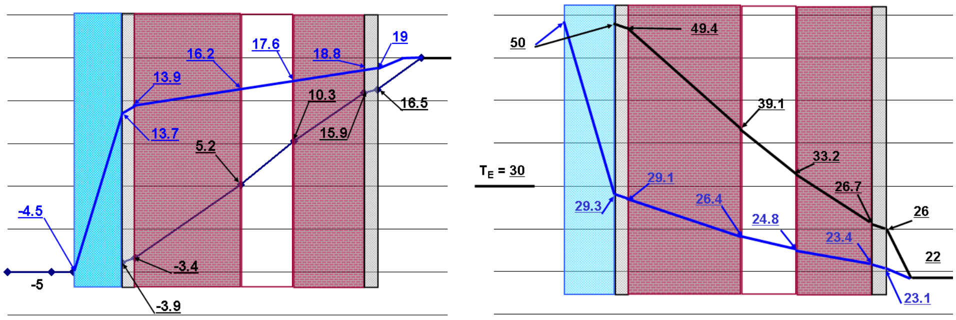


Figure 2: Reference wall stratigraphy

The heat losses for the reference wall were determined [1] considering the interior of a room maintained at 20°*C* in winter season and the presence of an insulating panel 80 mm thick. The evaluation has been performed also for the summer season according to the same methodology. The temperature profiles for both cases are reported in figures 3a and 3b.



a) Wintertime b) Summertime

Figure 3: Temperature profiles (blue line with ETICS, black line without ETICS)

The temperature profiles clearly show that the ETICS system allows the thermal gradients to be reduced inside the wall leafs. The reduced thermal gradient, proportional to the heat flux, highlights the beneficial effect of the ETICS on the energy saving.

This reduction leads also to mechanical benefits in terms of structural stresses in the masonry as explained below, but care must be taken on the performance of the adhesives to fix the panels.

4. STRESS WITHIN THE MASONRY

Any temperature difference in the masonries causes internal stresses [2]. The stress is due to the restrained thermal expansion or contraction and inflection.

The linear thermal expansion or contraction, $\nu = \lambda_m(T-T_r)$, of the masonry is due to the difference between the actual average temperature, T, inside the wall and a reference temperature, T_r, corresponding to zero stresses in the wall (building time temperature, assumed equal to about 20°C in the present work). The thermal expansion coefficient is λ_m and is assumed equal to 8 μm/m.

The thermal inflection, $\mu = \lambda_m(\Delta T/t_m)$ - being t_m the wall thickness - is due to the thermal gradient, ΔT, inside the wall given by the different temperature on the external - T_e - and internal - T_i - surface of each wall.

On safe side, it is assumed that the thermal deformation is fully restrained by the surrounding structure so that the axial load and bending moment - and the corresponding maximum stresses σ_N and σ_M - can be evaluated according to Eqs (1a) and (1b) assuming an elastic linear behavior for the material.

$$\sigma_N = \nu E_m \qquad \sigma_M = \pm \mu E_m t_m / 2 \quad \text{(1a,1b)}$$

In table 1a and 1b are reported the maximum stresses inside the external and internal walls, respectively. Tensile stresses are positive.

Table 1a – External wall

	Summer		Winter	
	With ETICS	W/out ETICS	With ETICS	W/out ETICS
T	27.8°C	44.2°C	15.0°C	0.9°C
ΔT	-2.7°C	-10.3°C	2.3°C	8.6°C
σ_N	-7 kPa	-23 kPa	5 kPa	18 kPa
σ_M	54 kPa	206 kPa	46 kPa	172 kPa
Max σ	47 kPa	183 kPa	51 kPa	190 kPa

Table 1b – Internal wall

	Summer		Winter	
	With ETICS	W/out ETICS	With ETICS	W/out ETICS
T_r	24.1°C	30°C	18.2°C	13.4°C
ΔT	-1.4°C	-6.5°C	1.2°C	6.2°C
σ_N	-3 kPa	-6 kPa	1 kPa	4 kPa
σ_M	28 kPa	130 kPa	24 kPa	124 kPa
Max σ	25 kPa	124 kPa	25 kPa	128 kPa

The stresses are higher in the external wall and the stresses due to the bending moments are predominant. Furthermore it can be seen that without the ETICS the stresses are relevant and can cause mechanical damages or even failures in tension. In the numerical example masonry with average compressive strength and Young Modulus, E_m, of about 5 MPa and 5 GPa, respectively, are considered. The maximum tensile stresses are reached during winter season and the presence of the ETICS is able to reduce them of about 75%, leading to high safety margins for the structure.

5. PEELING STRESS WITHIN THE ADHESIVE

The installation of the ETICS System reduces the temperature gradients in the masonry, because the main temperature gradient lies inside the insulating panel. This is the main reason for the stresses in the adhesives used to fix the panels to the masonry.

The typical stresses induced by the wind, for instance, are much lower than the stresses induced in the adhesives by the thermal effects. Even assuming an unrealistic extreme pressure drop - due to wind during a storm - equal to 1 atmosphere, the corresponding stress is about 101 kPa.

The masonry is assumed rigid if compared to the insulating panel, because the Young Modulus is about five hundred times higher. The adhesive is modeled as a series of independent normal springs smeared over the masonry with stiffness $k_a=E_a/t_a$, where E_a and t_a are the Young Modulus and the thickness of the adhesive, respectively. Each

insulating panel can be modeled separately due to the typical application mode: E_p and t_p are the Young Modulus and the thickness of the panel, respectively.
The equation governing the system (the sketch of half of the insulating panel and adhesive is reported in figure 4) is given by:

$$\left(\frac{E_p t_p^3}{12}\right)\frac{\partial^4 w}{\partial x^4}+k_a w=0 \quad (2)$$

The integral of the differential equation is:

$$w=e^{-\alpha x}\left[A\cos(\alpha x)+Bsin(\alpha x)\right]+e^{\alpha x}\left[C\cos(\alpha x)+Dsin(\alpha x)\right] \quad (3)$$

Where four constants (A, B, C, D) have to be determined and the parameter α - related to the characteristic length of the phenomenon 2π/α - is:

$$\alpha=\sqrt[4]{\frac{3k_a}{E_p t_p^3}} \quad (4)$$

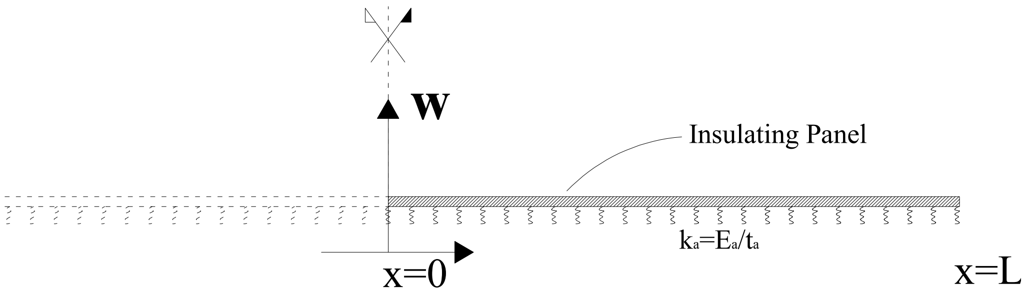


Figure 4: Sketch of half of the insulated panel

The boundary conditions are:

1. On the axis of symmetry (x=0) the rotation (δw/δx) and the shear force (proportional to $\delta^3 w/\delta x^3$) are zero due to symmetry.
2. At the end of the panel (x=L), where L is half length of the panel, the bending moment M (proportional to the elastic curvature $\delta^2 w/\delta x^2$) and the shear force are zero (condition at the free edge).

The total curvature in reality is the sum of the elastic component and the thermal component μ, according to the equation:

$$\frac{\partial^2 w}{\partial x^2} = \frac{M}{E_p t_p^3 / 12} + \mu \qquad (5)$$

The four boundary conditions lead to the definition of the four constants A, B, C, D as follows (assuming β = αL):

$$A = \frac{\mu \cdot e^{\beta}\left[e^{2\beta}\left(\cos\beta - \sin\beta\right) - \cos\beta - \sin\beta\right]}{2\alpha^2\left(e^{4\beta} + 4e^{2\beta}\cos\beta\sin\beta - 1\right)} \qquad (6a)$$

$$B = \frac{\mu \cdot e^{\beta}\left[e^{2\beta}\left(2\sin^2\beta - 1\right) - 2\cos\beta\sin\beta + 1\right]}{2\alpha^2\left(e^{4\beta} + 4e^{2\beta}\cos\beta\sin\beta\right)\left(\cos\beta - \sin\beta\right)} \qquad (6b)$$

$$C = \frac{\mu \cdot e^{\beta}\left[e^{2\beta}\left(2\cos\beta\sin\beta - 1\right) + 2\cos^2\beta - 1\right]}{2\alpha^2\left(e^{4\beta} + 4e^{2\beta}\cos\beta\sin\beta - 1\right)\left(\sin\beta - \cos\beta\right)} \qquad (6c)$$

$$D = \frac{\mu \cdot e^{\beta}\left[e^{2\beta}\left(2\cos^2\beta - 1\right) + 2\cos\beta\sin\beta - 1\right]}{2\alpha^2\left(e^{4\beta} + 4e^{2\beta}\cos\beta\sin\beta - 1\right)\left(\cos\beta - \sin\beta\right)} \qquad (6d)$$

In the following plots the values for the transverse displacement and bending moment of the panel, and the peeling stresses in the adhesive (positive are tensile stresses) are reported. The peeling stresses in the adhesive are evaluated as $k_a w$. The relevant geometrical and mechanical characteristics of the materials are reported in Table 2. The thermal gradient in the panel is the difference of temperature (related to the panel thickness) on the external and internal surface, assumed equal to -28°C and 20°C in summer and winter season, respectively.

Table 2 – Geometrical and mechanical characteristics

	Panel	Adhesive
Young Modulus	12 MPa	1200 MPa
Thickness	80 mm	4 mm
Thermal expansion λ_p	70 μm/m	*n.a.*
Half Length	625 mm	*n.a.*

Figure 5 (in winter season) shows the normal stress variation in the adhesive as a function of the distance form the center of the panel, as well as the transverse displacements of the panel. The stress concentration is at the free edge and the maximum tensile stress is found equal to 195 kPa, correspondingly the maximum transverse displacement of the panel is about 0.7 μm.

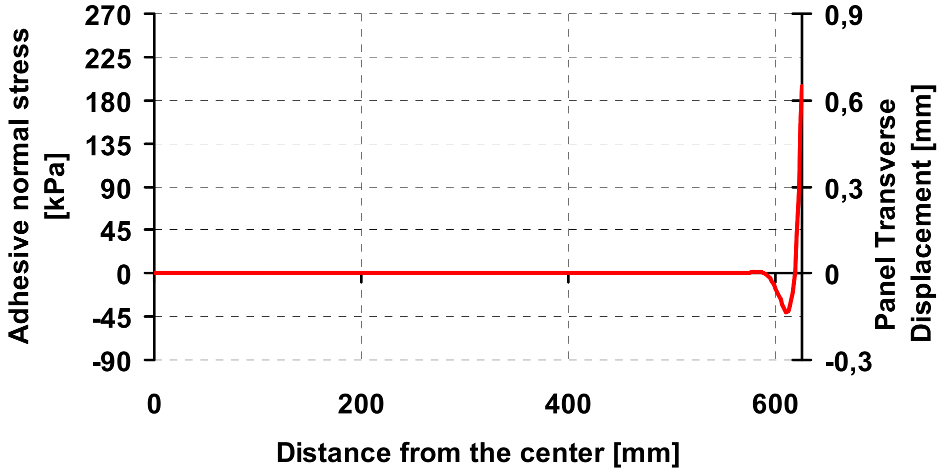


Figure 5: Adhesive normal stresses and panel transverse displacement in winter season

Figure 6 (in winter season) shows the bending moment variation in the panel as a function of the distance from its center. The bending moment is almost constant and it leads to a negligible stress ($6M/t_p^2$) in the panel of about 8 kPa.

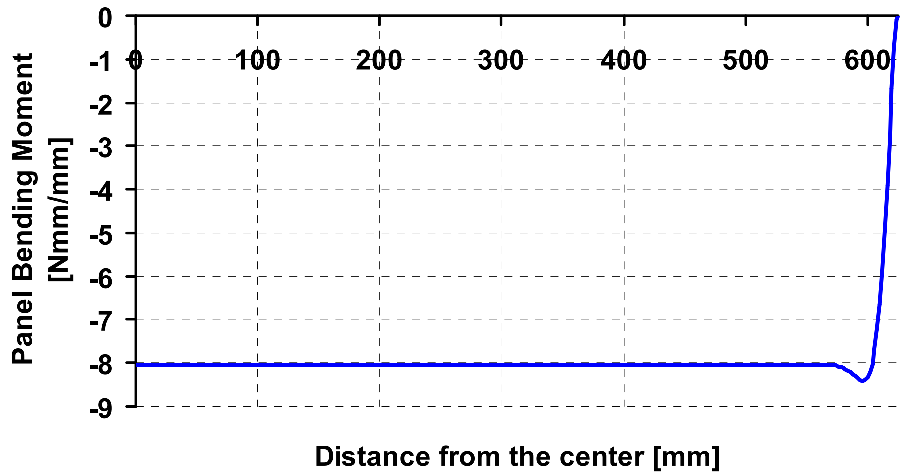


Figure 6: Bending moment in winter season

Figure 7 shows the equivalent of Figure 5 but in summer season. The stress concentration is at the free edge, but is in compression, while the maximum tensile stress is found equal to 63 kPa. The maximum transverse displacement of the panel is about 1 μm.

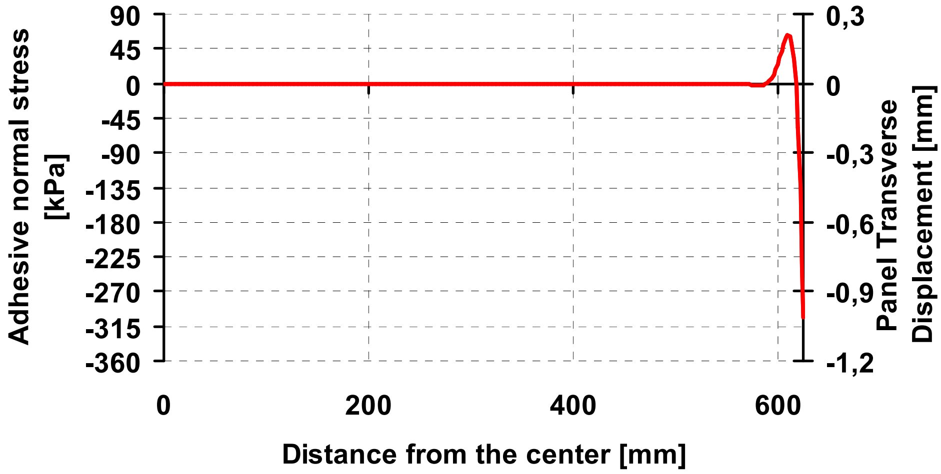


Figure 7: Adhesive normal stresses and panel transverse displacement in summer season

Figure 8 shows the bending moment variation in summer season. The bending moment is almost constant and it leads again to a higher, but still negligible, stress in the panel.

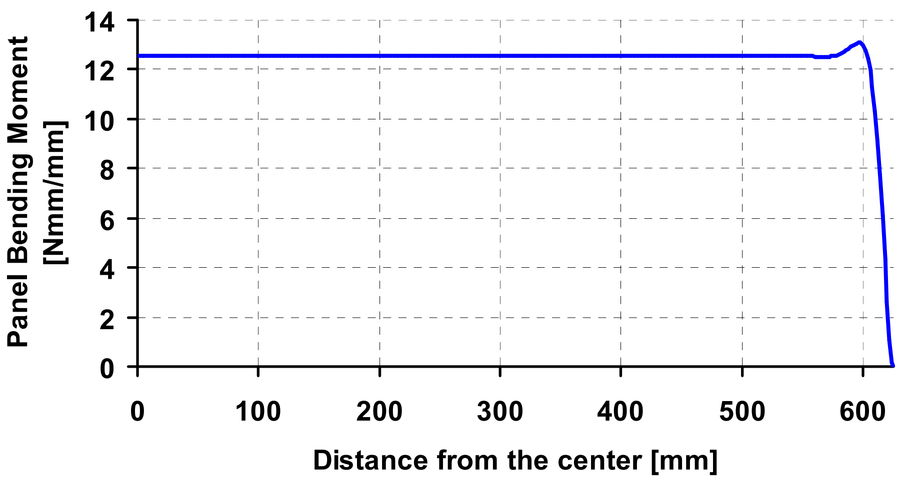


Figure 8: Bending moment in summer season

The comparison between summer and winter season seems to bring to the conclusions:

1. in the summer season, the peeling stress in the adhesive is generally lower than in winter season, appearing the winter season more critical;
2. the characteristic length of the phenomenon, $2\pi/\alpha$ is in this case about 57 mm, and consequently the only solicited portion of the adhesive is close to the edges of the panel;
3. the other, inner, portion of the panel is almost unloaded, so that a reduced application of the adhesive only along the perimeter of the panel seems safe;

These conclusions are misleading because in summer season the compression in the panel, due to the linear thermal expansion, is restrained thus leading to compression stability issues. The stability is crucial if the adhesive is applied only at the free edges of the panel. In this case the compression stress in the panel is rather close to the critical stress (according to Euler theory [2]). The compressed panel, in this case, can be assimilated to a simply supported beam 2L long.

5.1 Euler stability

The Young modulus of the panel is very low and, especially, the slenderness, $(2L\sqrt{12})/t_p$, of the panel is very high, so that the critical stress, σ_{cr}, may be rather low. It may be comparable or lower than the stress, σ_N (see Eq. (1a) substituting the corresponding properties of the panel), induced by the restrained linear thermal expansion. Only expansion (summer season) is crucial, while contraction, inducing tension, is stable. The critical stress is:

$$\sigma_{cr} = \frac{\pi^2 E_p t_p^2}{(2L)^2 \cdot 12} \qquad (7)$$

The critical stress is also highly related to the planarity of the panel and is reduced due to application defects.

It is remarked that the thermal stress is approximately independent on the thickness of the panel, while the critical stress is highly related to it, so that the smaller is the thickness of the panel, more critical is the stability failure. Assuming a $(T-T_r)=30°C$, the safety factor for stability in the case of 80 mm thick panel is 1.6, but in the case of 40 mm thick panel is 0.4, hence stability failure is predicted. Table 3 reports the outcomes of these analyses, being the safety factor the ratio σ_{cr}/σ_N. Considering the probability of defects, also a safety factor, higher than 1, but smaller than about 2, can be considered critical.

The application of the adhesive in a continuous layer and the care of planarity of the panel are the only ways to overcome these drawbacks. In fact the presence of the adhesive in a continuous layer (springs all over the length of the panel) yields to significantly higher values of the critical stresses [3].

Table 3 – Euler stability check

	80 mm Panel	40 mm Panel
Thermal stress, σ_N	25 kPa	25 kPa
Critical stress, σ_{cr}	40 kPa	10 kPa
Safety Factor	1.6	0.4

6. SHEAR STRESS WITHIN THE ADHESIVE

The linear thermal deformation of the panel leads also to shear stresses in the adhesive, close to the free edges. The evaluation of the maximum shear stress, τ_{max}, can be performed based on the shear lag theory [4] considering the axial load due to the restrained thermal deformation. The shear modulus of the adhesive, G_a, is assumed equal to 300 MPa.

$$\tau_{max} = \frac{\sigma_N}{\sqrt{\frac{t_a}{G_a}\frac{E_p}{t_p}}} \qquad (7)$$

Assuming again a $(T-T_r)=\pm 30°C$, the maximum shear stresses in both summer and winter seasons are reported in table 4 for 80 mm and 40 mm panels. Shear stresses are generally high so that a high quality adhesive specifically developed for this application must be used in order to guarantee the performance of the system.

Table 4 – Maximum shear stresses

	80 mm Panel	40 mm Panel
Thermal normal stress, σ_N	±25 kPa	±25 kPa
Maximum shear stress, τ_{max}	±650 kPa	±460 kPa

7. CONCLUSIONS

a) The ETICS System guarantees more than comfort and energy saving. It reduces of the stresses in the rear masonry walls. The stresses are higher in the external wall and the stresses due to the bending moments are predominant. The presence of the ETICS is able to reduce them of about 75%, leading to high safety margins for the structure.

b) The main temperature gradient lies inside the insulating panel. This is the main reason for the stresses in the adhesives used to fix the panels to the masonry.

c) The peeling stress in the adhesive is due to the restrained thermal inflection caused by the temperature gradient within the panel thickness. A model is proposed to evaluate these stresses: the main outcomes are that the most solicited portions of the adhesive are close to the panel edges, the maximum tensile stresses are relatively high and can be held only by high quality adhesives.

d) Even though the peeling stress in summer season seems to be lower than in winter, the restrained expansion of the panel yield to compression stress relevant if compared to the low critical (Euler) stress due to the high slenderness of the panels. The stability is more and more crucial for lower thicknesses of the panel. The application of the adhesive in a continuous layer and the care of planarity of the panel are the only ways to overcome these stability issues.

e) The linear thermal deformation of the panel leads also to shear stresses in the adhesive. Shear stresses are generally high so that a high quality adhesive specifically developed for this application must be used in order to guarantee the performance of the system.

The results of the analyses, carried out in this paper, clearly show the added value of the ETICS System. The advantages, not limited to the energy saving, make the investment related to the ETICS System installation attractive from the economic and financial point of view. The critical issues strongly suggest the application of the whole system designed and realized by a reliable supplier.

8. REFERENCES

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