A DATABASE OF Z-TRANSFORM COEFFICIENTS FOR MEDITERRANEAN BUILDING TYPOLOGIES.

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ABSTRACT

This work wants to provide the planners with a database of the typical mediterranean building structures. This provides a set of coefficients of the transfer functions which describe exactly the thermal behaviour of the structure, the time lag and the attenuation of the heat flux. For each structure is individualised the best number of coefficients and roots to assure the reliability of the thermal simulation. The attention is mostly upon the structures with high values of thermal inertia which are typical structures of the mediterranean buildings and also of building with bulkhead built in ages preceeding the usage of the reinforced concrete.

INTRODUCTION

An energetic oriented choice of building materials assumes a remarkable importance because it permits to reach, from the first stages of the planning, the energetic saving aims and the best condition of comfort. In this way, the free solar contribution can be better used.

It is very important for the planners to have a technical aid during the selection of the suitable type of structure to the particular meteoclimatic situation where the considered building shall stand.

The ASHRAE procedure called “Transfer Functions Method” (TFM), common during the planning of air condition system, analyses the transfer heat problems in non-steady-state solicited by discrete input signals utilising the Z-transform (ZT). The ZT is in fact an algorithm particularly suitable in the case of climatic input known with fixed sampling period.

The validity of the TFM is now commonly accepted but its exact application to building typologies, different from those typical in the U.S., requires a particular attention. [1,2]

The TFM had in Italy a limited diffusion because of the scarce adaptability of the data (included in the tables of the ASHRAE manual) to the building typologies traditionally used in our country.

In previous paper [3] authors underlined how the most diffused commercial software for the simulation of the thermal behaviour in non-steady-state of the room don’t assure the exact determination of the transfer function coefficients for each building structure. Some of them don’t assure the reliability of the coefficients for building structures which are made up of elements not considered by the ASHRAE manual. This limit is clearly shown in user manual [5]. It is fundamental to have a theoretic verification model of the coefficient reliability.

It is meanwhile important the creation of a database of building structures more adherent to the Mediterranean typologies which are notoriously characterised by higher mass and higher values of thermal inertia than those ones traditional of the United States.

The database of the building structures typical of the Mediterranean area is described in this paper.

To define in a simple and immediate way the composition of the multilayers structure, the database contains the thermophysical characteristics of the simple building elements which are contained in UNI 10351 and 10355 (Italian Standards). These data have been integrated with those originated from an research concerning the most representative building typologies that may be found in the urban area of Palermo, individualised during the compiling of the Municipal Energetic Plan.

In the database, for each building structure, is reported the number of coefficients and poles used, the sampling period of the input signal, the different forms of interpolations of the input signal and an index, later described, representative of the error linked to the number of coefficients and poles used.

METHODOLOGY

The non–steady–state heat problems in multilayers walls is described by a set of differential equations which can be solved by mathematic operators reaching the matrix:

$$\begin{vmatrix} T_e \\ Q_e \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \times \begin{vmatrix} T_i \\ Q_i \end{vmatrix} \qquad (1)$$

in which T and Q are, in this case, Laplace transform (LT) of the temperatures t_i and t_e and of the heat fluxes q_i and q_e in correspondence of the inside and outside surfaces of the wall, while *A*, *B*, *C* and *D* are the coefficients of the wall transmission matrix reached through the product of transmission matrixes, of each *n* layers forming the wall:

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \prod_{m=1}^{n} \begin{vmatrix} a_m & b_m \\ c_m & d_m \end{vmatrix} \qquad (2)$$

a_m b_m c_m d_m are respectively:

$$a_m = \cosh\left(L\sqrt{\frac{s}{\beta}}\right)$$

$$b_m = \frac{\operatorname{senh}\left(L\sqrt{\frac{s}{\beta}}\right)}{\lambda\sqrt{\frac{s}{\beta}}} \qquad (3)$$

$$c_m = \lambda\sqrt{\frac{s}{\beta}} \cdot \operatorname{senh}\left(L\sqrt{\frac{s}{\beta}}\right)$$

$$d_m = a_m$$

$$\beta = \frac{\lambda}{\rho C_p}$$

and the used symbols have, for each *m* layer, the following meaning:

λ thermal conductivity $\left[\frac{W}{mK}\right]$

ρ density $\left[\frac{kg}{m^3}\right]$

C_P specific heat $\left[\frac{kJ}{kgK}\right]$

L thickness $[m]$

The system can be described using the ZT at the LT place. For a time-continuous $f(t)$, with sampling period Δ, LT is,:

$$f(0) + f(\Delta)e^{-s\Delta} + f(2\Delta)e^{-2s\Delta} + \ldots \qquad (4)$$

Supposing $e^{s\Delta} = z$

We obtain:

$$f(0)z^0 + f(\Delta)z^{-1} + f(2\Delta)z^{-2z} + \ldots, \qquad (5)$$

That is the ZT of the function $f(t)$.

If a system is solicited by an input signal whose ZT is $I(z)$ and the output is $O(z)$, the link we have to determine is:

$$\frac{O(z)}{I(z)} \qquad (6)$$

If the system is individualised by a transfer function $G(s)$, where $I(s)$ and $O(s)$ are the LT of input and output:

$$H(z) = \frac{O(z)}{I(z)} = \frac{Z[O(s)]}{Z[I(s)]} = \\ = \frac{Z[I(s) \cdot G(s)]}{Z[I(s)]} \qquad (7)$$

As we notice from this last equation, the link between input and output is always influenced by the kind of employed input and therefore we can obtain as many different $H(z)$ as the possible input function. When we have time series of the air-sol temperature values t_e, sampled with an interval Δ, and the temperature of the inner air is known and constant, the emerging thermal flux q_i at the generic instant $n\Delta$ can be calculated with the following recursive equation:

$$q_i(nT) = q_{i,n} = \\ = \sum_{j=0}^{n} b_j t_{e,(n-j)} - \sum_{j=1}^{n} d_j q_{i,(n-j)} - \sum_{j=0}^{n} c_j t_{i,(n-j)} \qquad (8)$$

The coefficients can be considered similar to the transfer functions of the system even if they directly depend on the function chosen to interpolate two following values of t_e.

It has been observed that for interpolator functions of order higher than the first we find in the system responce, an oscillatory component which doesn't permit the determination of the coefficients useful to the application of the ASHRAE procedure.

For this reason the database reports the transfer functions coefficients which are calculated for interpolator ramp functions and interpolator step functions.

The software used for the creation of the database is called TH.EL.D.A (Thermal Elements Dynamic Analysis) [4].

This tool presents characteristic of flexibility and innovation respect to the softwares mostly diffused for the analysis of the dynamic thermal behaviour of building multilayers structures. As a matter of fact TH.EL.DA. allows to introduce different levels of precision in the individualisation of the transfer coefficients. Related to the previous theoretic consideration, it is possible to adapt the input parameter (number of poles, number of coefficients, different sampling period) considering the time lag of the walls. In detail, the advantages linked with the use of the software are the following:

- The user can create his own database of coefficients of transfer functions for the multilayers building structures mostly used in its own area.
- The time lag and the attenuation factor, typical of a building structure, permit the planner to operate a previous choice of the materials forming the building covering, bettering the usage of free solar contributions over the opaque surfaces in relation to the wished time lag.
- The set of the coefficients of the transfer functions can be re-used for new simulations or they can be employed in other softwares such us TRNSYS.
- One can introduce different levels of precision in the individualisation of the transfer coefficients, adapting the input parameters (number of poles, number of coefficients and sampling period) related to the analysed wall.
- Then, the reliability of coefficients is tested by an error index.

The use of different input parameters permits to obtain different sets of coefficients useful to describe the behaviour of the system, offering different levels of accuracy and simplicity of calculation. The different set of coefficient of the transfer functions related to the step input and to the linear ramp input, are obtained respectively with the following equations. For step input:

$$\begin{cases} I(s) = \dfrac{1}{s} \\ O(s) = \dfrac{C_o}{s} + \displaystyle\sum_{n=1}^{\infty} \dfrac{d_n}{s+\beta_n} \\ o(t) = C_0 + \displaystyle\sum_{n=1}^{\infty} d_n e^{-\beta_n t} \\ I(z) = \dfrac{1}{1-z^{-1}} \\ O(z) = \dfrac{N(z)}{D(z)} I(z) = \\ = \dfrac{C_0}{1-z^{-1}} + \displaystyle\sum_{n=1}^{\infty} \dfrac{d_n}{1-e^{\beta_n \Delta} z^{-1}} \end{cases} \tag{9}$$

where, indicating with *s*, *t*, and *z* respectively the LT variable, time, and the ZT variable:

$$\begin{cases} C_0 = \left[\dfrac{A(s)}{B(s)} \right]_{s=0} \\ d_n = \left[\dfrac{A(s)}{sB'(s)} \right]_{s=-\beta_n} \\ B'(s) = \dfrac{d}{ds} B(s) \end{cases} \tag{10}$$

β_n are the roots or poles of $B(s) = 0$ and Δ the sampling interval.

Linear ramp input

$$\begin{cases} I(s) = \dfrac{1}{s^2} \\ O(s) = \dfrac{C_o}{s^2} + \dfrac{C_1}{s} + \displaystyle\sum_{n=1}^{\infty} \dfrac{d_n}{s+\beta_n} \\ o(t) = C_0 t + C_1 + \displaystyle\sum_{n=1}^{\infty} d_n e^{-\beta_n t} \\ I(z) = \dfrac{1}{z\left(1-z^{-1}\right)^2} \\ O(z) = \dfrac{C_0 \Delta}{z\left(1-z^{-1}\right)^2} + \dfrac{C_1}{1-z^{-1}} + \displaystyle\sum_{n=1}^{\infty} \dfrac{d_n}{1-e^{\beta_n \Delta} z^{-1}} \end{cases} \tag{11}$$

where:

$$\begin{cases} C_1 = \left[\dfrac{A'(s)B(s) - A(s)B'(s)}{B(s)^2} \right]_{s=0} \\ d_n = \left[\dfrac{A(s)}{s^2 B'(s)} \right]_{s=-\beta_n} \\ A'(s) = \dfrac{d}{ds} A(s) \end{cases} \qquad (12)$$

In order to evaluate the accuracy of the calculations carried out by using a given set of ZT coefficients, we have to compare them with a reference response coming from a procedure having a different mathematical background and even able to give the time continuous response of the system. Thus, in order to evaluate the reference response if we want to control the reliability of the coefficients sets evaluated by mean of diverse input signals we have to:

- Using input signals having the typical time variation of the physical phenomena and then avoid steps, ramps, and other not physically possible signals.
- Adopt an evaluating approach which differs from that employed to calculate ZT coefficients sets, and then exclude Laplace Transform (LT).

It has been necessary, to perform this analysis, to define for the t_e temperature or any generic input signal, a rule of interpolation able to reproduce a physic realistic behaviour starting from the sampled data. So, the input signal it has been represented by the function $X(t)$, which is not discrete within the generic interval of sample t_n, t_{n+1} defined by the expression:

$$X(t) = at^3 + bt^2 + ct + d \qquad (13)$$

in which the coefficients *a, b, c, d* are calculated imposing the following constraints:

1) the $X(t)$ assumes the values $X(t_n)$ and $X(t_{n+1})$

2) the tangent to the curve at the point $\left[t_n,\ X(t_n)\right]$, forms equal angles with the segments joining $X(t)$ to $X(t_{n-1})$ and $X(t_n)$ to $X(t_{n+1})$

In periodic steady state any wave $f(t)$ with period *T* can be analysed into the sum of sinusoidal waves of different frequencies:

$$f(t) = \frac{1}{2}a_0 + \sum_{n-1}^{\infty}\left[a_n \cos(n\omega t) + b_n \sin(n\omega t)\right] \quad (14)$$

Supposing that $f(t)$ is known in correspondence to the *N* instants in which the period *T* was subdivided, coefficients are:

$$\begin{cases} a_0 = \dfrac{2}{N}\displaystyle\sum_{k=0}^{N-1} f\left(\dfrac{kt}{N}\right) \\ a_n = \dfrac{2}{N}\displaystyle\sum_{k=0}^{N-1} f\left(\dfrac{kt}{N}\right)\cdot \cos\left(\dfrac{2\pi kn}{N}\right) \\ b_n = \dfrac{2}{N}\displaystyle\sum_{k=0}^{N-1} f\left(\dfrac{kt}{N}\right)\cdot \mathrm{sen}\left(\dfrac{2\pi kn}{N}\right) \end{cases} \qquad (15)$$

Then, calculating the time response to each harmonic component and recombine all of them, one can obtain the system response to the generic $f(t)$.

So, in relation to the different forms of the employed signals, the calculated fluxes have been compared to those ones obtained by Fourier's analysis in periodic steady state conditions. As the ASHRAE procedure for air conditioning cooling load takes into account the hourly values of inside heat gains, we founded the comparison on the percentage mean error parameter EMP:

$$EMP = \frac{1}{24}\sum_{\tau=1}^{24} \frac{\left|Q_Z(\tau) - Q_F(\tau)\right|}{Q_F(\tau)} \cdot 100 \qquad (16)$$

where Q_Z and Q_F are the hourly inside heat fluxes at generic time τ calculated using the ZT and the Fourier analysis respectively. To exit from transient response, the calculation with ZT is recursive until signal is stabilised.

ANALYSIS

A deepening has been done to find the best number of poles to employ in the calculation and the best number of ZT coefficients (theoretically infinite) to employ in the transfer function of the wall. Some criteria have been formulated to choose the sampling period. One can observe that when the time lag of a wall is bigger, the number of coefficients used to reach a good precision is bigger too. We have found that it is better to group the examined walls in three classes with a time lag inferior than 5 hours, between 5 and 12 hours, and superior than 12 hours.

From the carried elaboration comes out:

- Concerning the poles, one has verified that the passage from 100 to 1000 poles in the procedure of calculation provokes variation in the EMP inferior than 1% in the step entrance, more contained in the ramp entrance
- Under the same conditions the second walls class presents a lower EMP. The best number of coefficients to use is 7 (n = 0, 1,…,6)
- For the third class walls the addition of only one coefficient (implied coefficient ugual to 8, n = 0, 1,…,7) reduces drastically the *EMP*. The minimum number of coefficients that have to be employed is six. In the second and third class walls, another growing of the number of coefficients produces another reduction of EMP, even if this effect is now scarcely perceptible.
- The error concerning the first class walls is independent from the number of coefficients. For low values of the time lag the necessary number of coefficients is less than those normally employed. The EMP is, indeed, linked to the sample period of input signal. It has been in fact, founded that the reduction of the EMP is obtained doubling the sampling frequency both with the ramp linear input and with the step input. Then, for low time lag walls, it is necessary to increase the sampling frequency of solicitation.

In order to show the information stored in the database, some data are reported; these are referred to the walls belonging to the classes just mentioned. In particular the thermophysical characteristic of the layers are reported in the table n. 1, on the other hand in table n. 2 the composition of the walls is reported, and in table n. 3 the variation of the EMP, when the number of the roots and coefficients varies, is described.

In the figures n. 1 and n. 2 one can observe how the best number of roots and coefficients to use in the calculation for the following simulation, is given.

Table n. 1: thermophysical characteristic of the layer.

Code	$L \cdot 10^{-3}$	λ	C_p	ρ	R
E1	20	0.727	0.84	1602	0.84
UNI3	425	0.72	0.84	1800	0.54
UNI5	250	0.72	0.84	1800	0.32
UNI37	88	0.24	0.88	800	0.3

Table 2: composition of the walls.

Code	Inside layer	Medium layer	Outside layer
WallA	E1	UNI3	E1
WallB	E1	UNI5	E1
WallC	E1	UNI37	E1

Table 3: variation of EMP.

Wall	Roots	Coeff.	EMP ramp	EMP step
WallA	100	9	0,10	0,20
	100	8	0,10	0,20
	100	7	0,09	0,23
	100	6	1,72	4,83
	100	5	3,31	59,70
	500	9	0,10	0,03
	700	9	0,10	0,04
	1000	9	0,10	0,09
	50	9	0,10	0,79
	25	9	0,11	3,03
	10	9	1,40	12,99
WallB	100	9	0,41	0,27
	100	8	0,41	0,27
	100	7	0,41	0,27
	100	6	0,41	0,27
	100	4	0,56	3,59
	100	5	0,41	0,26
	100	3	29,62	95,77
	700	9	0,41	0,17
	50	9	0,41	0,56
	25	9	0,40	1,42
	10	8	0,70	8,66
WallC	100	9	3,56	2,53
	100	8	3,56	2,53
	100	7	3,56	2,53
	100	6	3,56	2,53
	100	5	3,56	2,53
	100	3	3,56	2,53
	100	4	3,56	2,53
	100	3	3,56	2,53
	100	2	3,11	5,01
	300	9	3,56	2,40
	500	9	3,56	2,39
	700	9	3,56	2,38

	1000	9	3,56	2,38
	50	9	3,56	3,05
	25	9	3,56	0,83
	10	9	3,58	16,90

CONCLUSIONS

The application of the dynamic simulation methods to analyse buildings energetic behaviour founded upon ZT require a better characterisation of the coefficients that describe Mediterranean building typologies.

In particular the coefficients contained in the tables edited by ASHRAE result inadequate to describe the building constructive typologies used in the south of Europe, and characterised by very different materials and thickness than those ones used in the Anglo-Saxon world.

The code of calculus permits to introduce profiles of air-sol temperature defined by the user and it also permits to choose different levels of precision in the individualisation of the transfer coefficients, adapting the input data (number of roots and intervals of sample) to the thermophysical characteristics of the wall.

In this paper criteria of selection of the best number of coefficients of ZT have been defined; they are used in the dynamic simulation of the multilayers building structures. With the aid of the code of calculation, the coefficients of the transfer function of structures composed by building components contained in the catalogue UNI 10355 and UNI 10351, together with the building elements included in the census of the Municipal Energetic Plan of Palermo have been determined. This happens because one think that the just mentioned components are more adherent to the thermophysical characteristic of the national building manufacts and they can constitute a first reference for the following creation of a thermophysic catalogue of the walls mostly used in the Mediterranean area. The constituted database is a good help for the planner because it individualises the number of the coefficients and poles good for simulation. These information permit to provide the user an energetic awareness in the choice of materials and the possibility to appreciate the effects of the modification of input data in the simulated transient.

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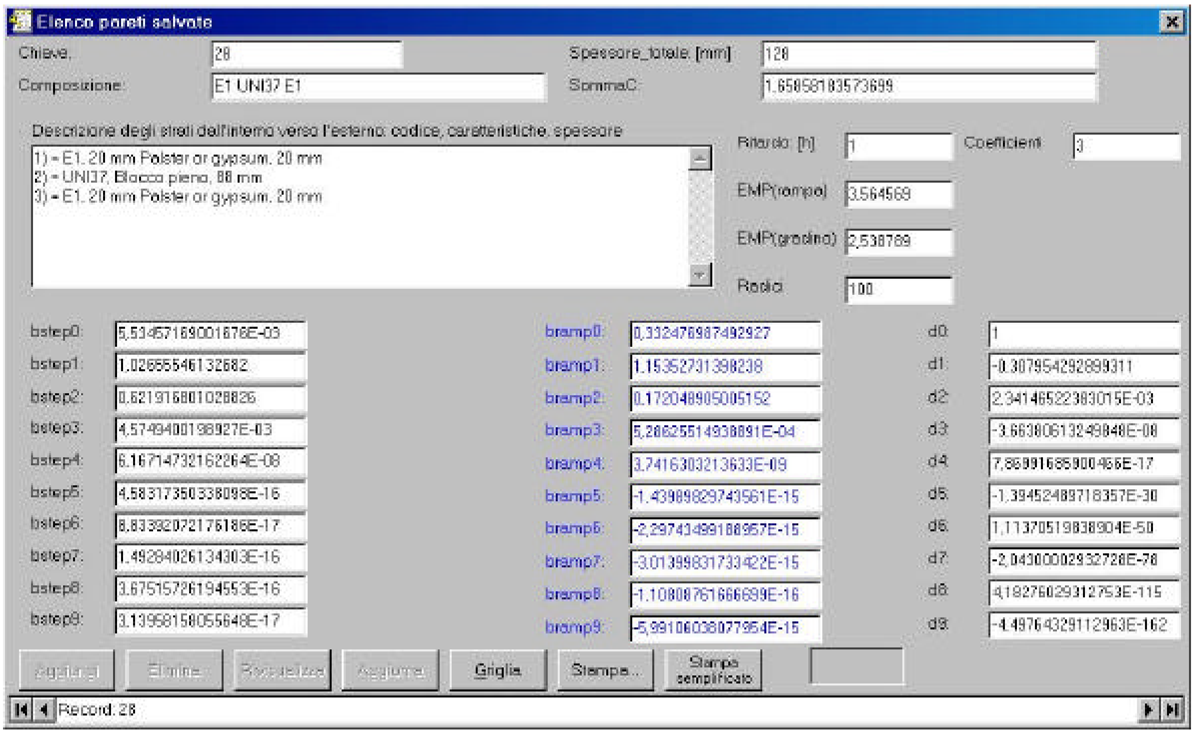
Figure 1: multilayers walls belonging to the first class



Chiave: 28
Composizione: E1 UNI37 E1
Spessore_totale: [mm] 128
SommaC: 1,65858183573699

Descrizione degli strati dall'interno verso l'esterno: codice, caratteristiche, spessore

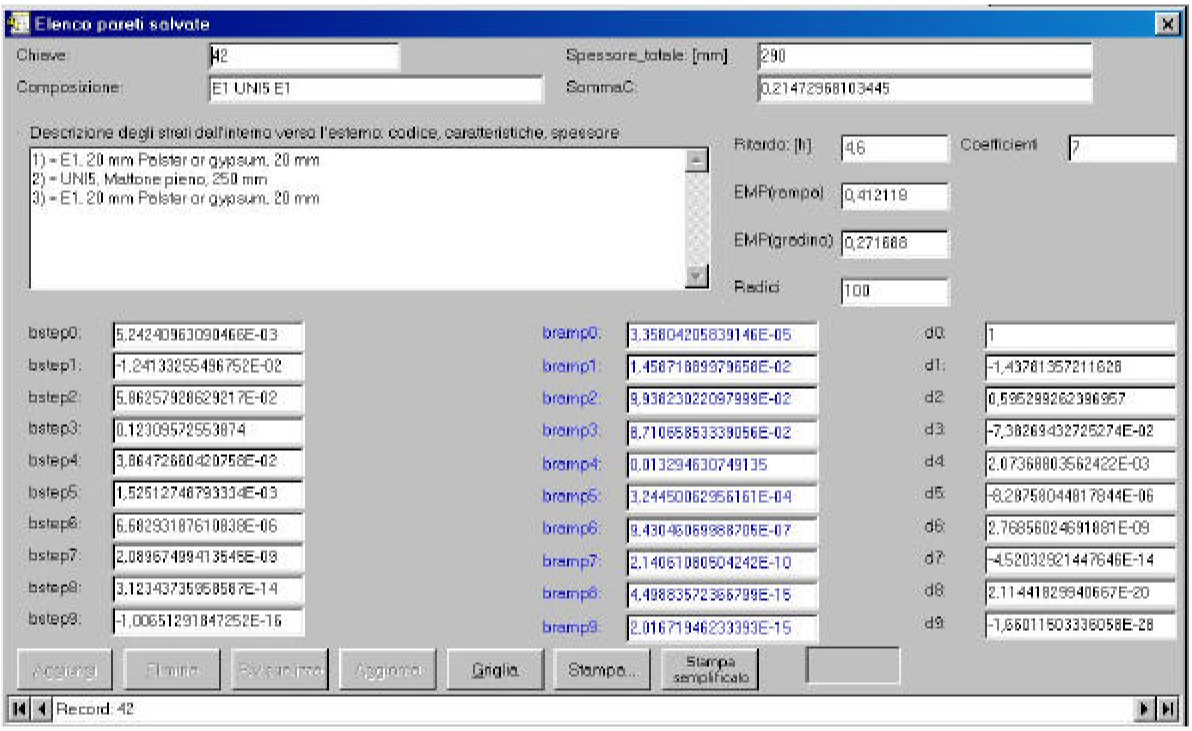
1) - E1. 20 mm Plaster or gypsum. 20 mm
2) - UNI37, Blocco pieno, 88 mm
3) - E1. 20 mm Plaster or gypsum. 20 mm

Ritardo: [h] 1
Coefficienti 3
EMP(rampa) 3,564569
EMP(gradino) 2,538789
Radici 100

bstep0:	5,53457169001876E-03	bramp0:	0,332476987492927	d0:	1
bstep1:	1,02655546132682	bramp1:	1,15352731398238	d1:	-0,307954292899311
bstep2:	0,621916801028826	bramp2:	0,172048905005152	d2:	2,34146522383015E-03
bstep3:	4,5749400198927E-03	bramp3:	5,28625514938891E-04	d3:	-3,66380613249848E-08
bstep4:	6,16714732162264E-08	bramp4:	3,7416303213633E-09	d4:	7,86991685900466E-17
bstep5:	4,58317350338098E-16	bramp5:	-1,43989829743561E-15	d5:	-1,39452489718357E-30
bstep6:	8,83392072176186E-17	bramp6:	-2,29743499188957E-15	d6:	1,11370519838904E-50
bstep7:	1,49284026134303E-16	bramp7:	-3,01399831733422E-15	d7:	-2,04300002932728E-78
bstep8:	3,67515726194553E-16	bramp8:	-1,10808761666699E-16	d8:	4,18276029312753E-115
bstep9:	3,13958158055648E-17	bramp9:	-5,99106038077954E-15	d9:	-4,49764329112963E-162

Record: 28

Figure 2: multilayers walls belonging to the second class



Chiave: 42
Composizione: E1 UNI5 E1
Spessore_totale: [mm] 290
SommaC: 0,21472968103445

Descrizione degli strati dall'interno verso l'esterno: codice, caratteristiche, spessore

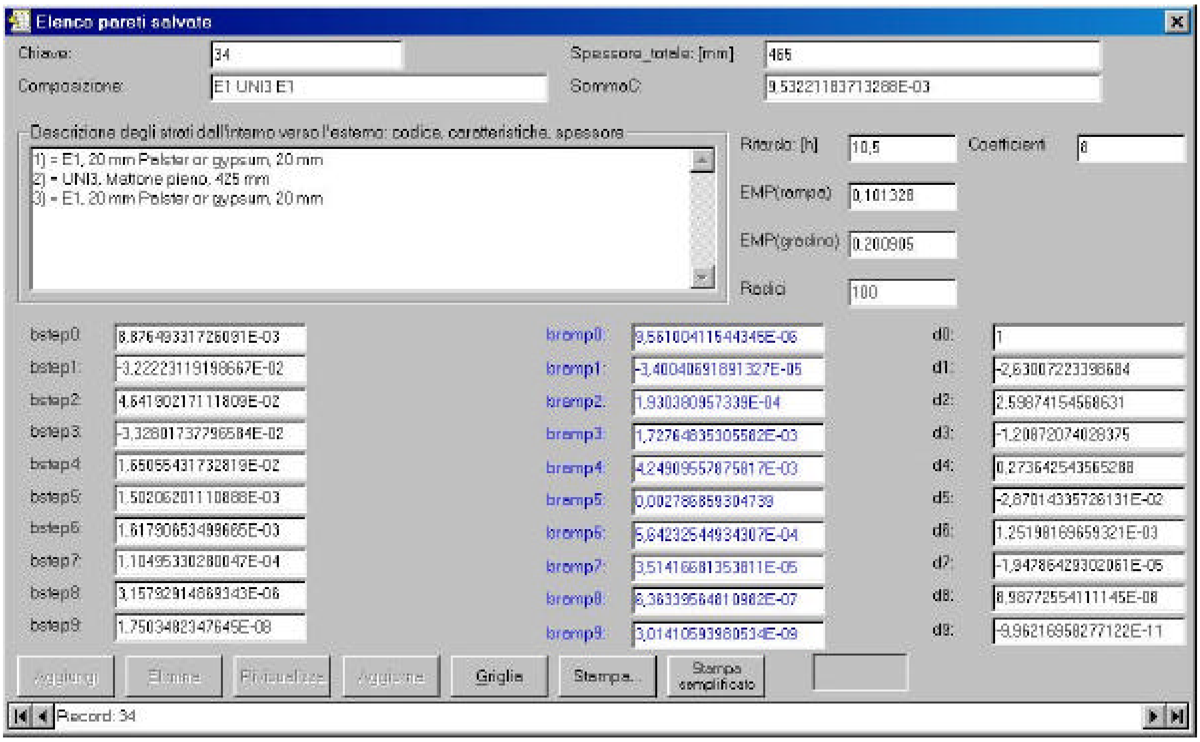
1) - E1. 20 mm Plaster or gypsum. 20 mm
2) - UNI5, Mattone pieno, 250 mm
3) - E1. 20 mm Plaster or gypsum. 20 mm

Ritardo: [h] 4,6
Coefficienti 7
EMP(rampa) 0,412118
EMP(gradino) 0,271688
Radici 100

bstep0:	5,24240963090466E-03	bramp0:	3,35804205839146E-05	d0:	1
bstep1:	-1,24133255496752E-02	bramp1:	1,45871889979858E-02	d1:	-1,43781357211628
bstep2:	5,86257928629217E-02	bramp2:	9,93823022097999E-02	d2:	0,595299262396957
bstep3:	0,12309572553874	bramp3:	8,71065853339056E-02	d3:	-7,38269432725274E-02
bstep4:	3,86472880420758E-02	bramp4:	0,013294630749135	d4:	2,07368803562422E-03
bstep5:	1,52512748793334E-03	bramp5:	3,24450062956161E-04	d5:	-8,28758044817844E-06
bstep6:	6,68293187610838E-06	bramp6:	9,43046069988705E-07	d6:	2,76856024691881E-09
bstep7:	2,08967499413545E-09	bramp7:	2,14061080504242E-10	d7:	-4,52032921447646E-14
bstep8:	3,12343735958587E-14	bramp8:	4,49883572366799E-15	d8:	2,11441829940667E-20
bstep9:	-1,00651291847252E-16	bramp9:	2,01671946233393E-15	d9:	-1,66011503336058E-28

Record: 42

Figure 3: multilayers walls belonging to the third class



Chiave: 34

Composizione: E1 UNI3 E1

Spessore_totale: [mm] 465

SommaC: 9,53221183713288E-03

Descrizione degli strati dall'interno verso l'esterno: codice, caratteristiche, spessore

1) = E1, 20 mm Palster or gypsum, 20 mm
2) = UNI3, Mattone pieno, 425 mm
3) = E1, 20 mm Palster or gypsum, 20 mm

Ritardo: [h] 10,5

Coefficienti 8

EMP(rampa) 0,101328

EMP(gradino) 0,200905

Radici 100

bstep0:	8,87649331726091E-03	bramp0:	9,56100411544346E-06	d0:	1
bstep1:	-3,22223119198667E-02	bramp1:	-3,40040691891327E-05	d1:	-2,63007223398684
bstep2:	4,64190217111809E-02	bramp2:	1,930380957339E-04	d2:	2,59874154568631
bstep3:	-3,32801737796584E-02	bramp3:	1,72764835305582E-03	d3:	-1,20872074028375
bstep4:	1,65055431732819E-02	bramp4:	4,24909557875817E-03	d4:	0,273642543565288
bstep5:	1,50206201110888E-03	bramp5:	0,002786859304739	d5:	-2,87014335726131E-02
bstep6:	1,61790653499665E-03	bramp6:	5,64232544934307E-04	d6:	1,25198169659321E-03
bstep7:	1,10495330280047E-04	bramp7:	3,51416681353811E-05	d7:	-1,94786429302061E-05
bstep8:	3,15792914869343E-06	bramp8:	6,36339564810982E-07	d8:	8,98772554111145E-08
bstep9:	1,7503482347645E-08	bramp9:	3,01410593980534E-09	d9:	-9,96216958277122E-11

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