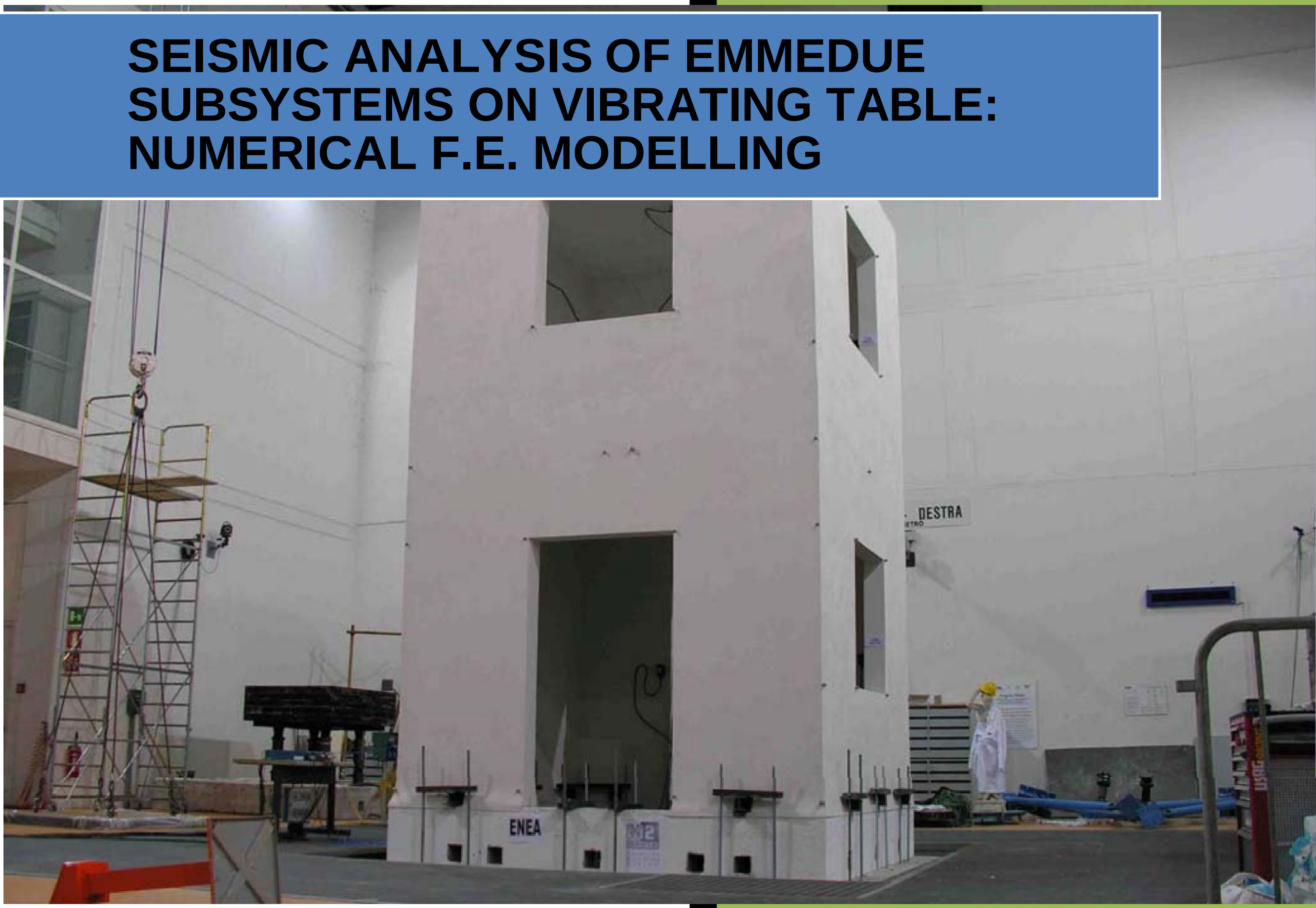
Italian National Agency for
New Technologies, Energy
and the Environment

ENEA – EMMEDUE agreement
Checking and validation of static and seismic behaviour of buildings constructed using the EMMEDUE system by means of experimental tests

SEISMIC ANALYSIS OF EMMEDUE SUBSYSTEMS ON VIBRATING TABLE: NUMERICAL F.E. MODELLING



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ENEA – ACS

February 2009

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1 INTRODUCTION

This report is part of the agreement drawn up between EMMEDUE and ENEA for the "Checking and validation of static and seismic behaviour of buildings constructed using the EMMEDUE system by means of experimental tests", dated 10/10/2007, which envisaged the following activities as the responsibility of ENEA:

- Dynamic tests on 2 subsystems on vibrating table,
- Evaluation and guidelines,
- Coordination of the whole project.

The experimental phase on the vibrating table, in fact, consisted of testing 3 subsystems:

1) one subsystem, C-shaped in plan, composed of a wall which is 2.70 *m* high and 3.00 *m* long, with two wall sections at the ends, which are 1.00 *m* long, and a flat roof element on top;
2) one subsystem, H-shaped in plan, composed of a wall which is 2.70 *m* high and 3.00 *m* long, with two wall sections at the ends, which are 1.00 *m* long, and a flat roof element on top;
3) one subsystem composed of four perimeter walls, two of which with door openings, one with a window opening and one with no opening, each with a plan length of 3.40 *m* (excluding edging) and an overall height of 5.74 *m* (excluding edging), with a flat roof at the top and an intermediate floor, in order to simulate a section of the two-storey building with a scale which is equal or near to the actual one.

The samples were all manufactured by EMMEDUE at the Dynamic Tests Laboratory of the Casaccia research centre between 14/07 and 08/08/2008. The tests were conducted between 20-24/10/2008 (case 1), 27-31/10/2008 (case 2), 24-27/11/2008 (case 3).
This report provides the calculations made to support the experimental phases of the three models.

2 2-STOREY BUILDING

2.1 Model

The model tested on the vibrating table reproduces a two-storey house, limited to a single environment. The objective is to check the dynamic behaviour in the presence of seismic actions, measuring the response of the structure in terms of accelerations and displacements. Figures 1, 2, 3 and 4 show plans, elevations and cross sections of the model, produced by EMMEDUE using ENEA information, on the basis of which the model at the Dynamic Tests Laboratory of the Casaccia research centre was created.

FOUNDATION PLAN

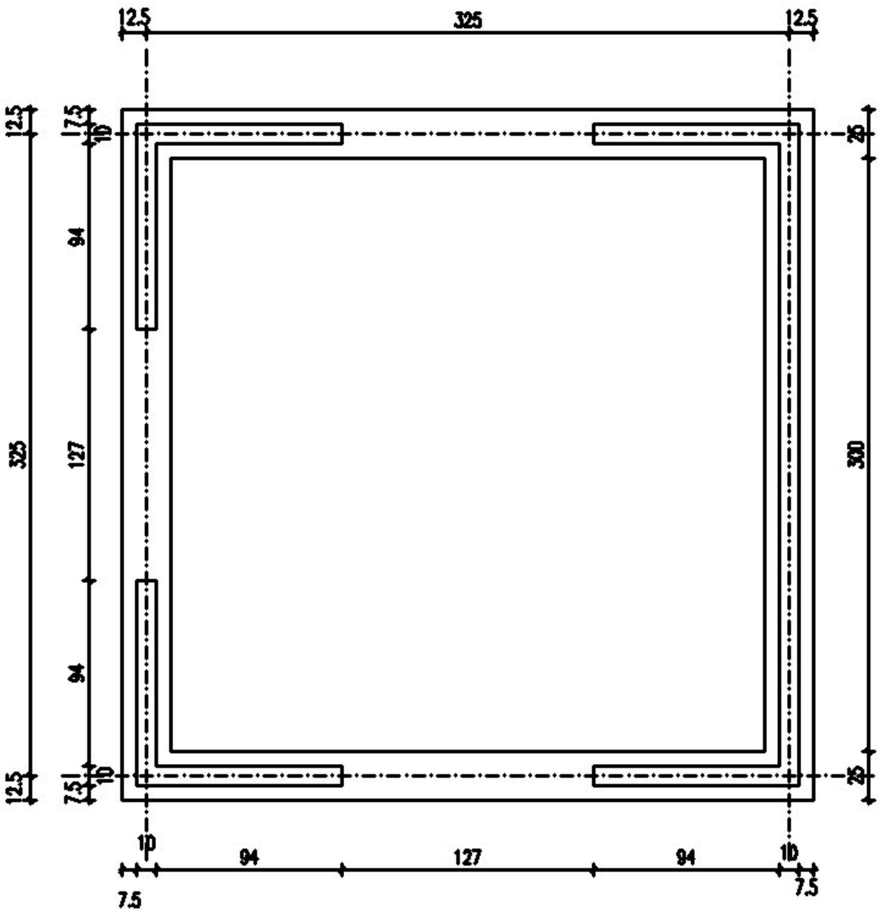


Figure 1a

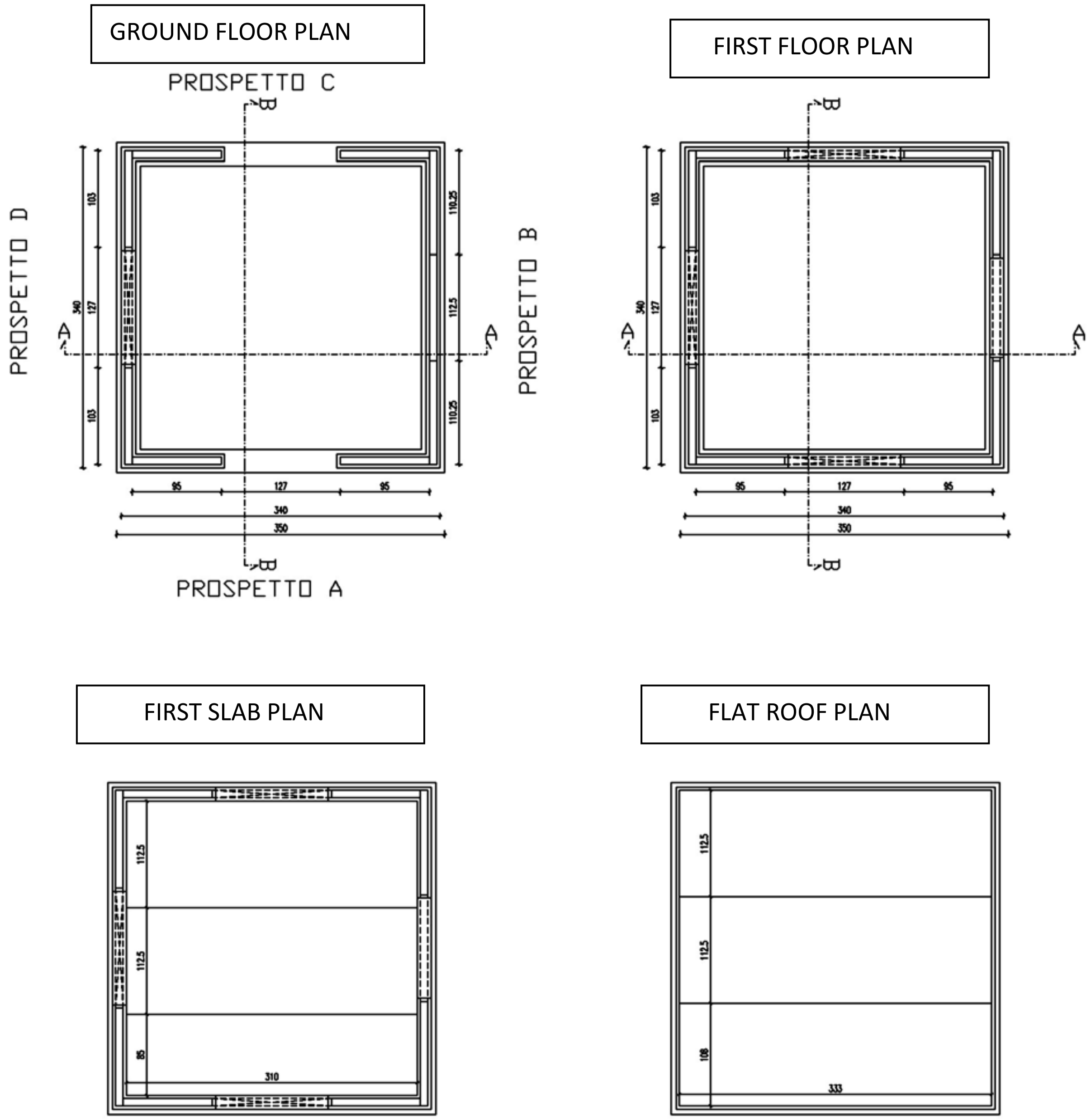
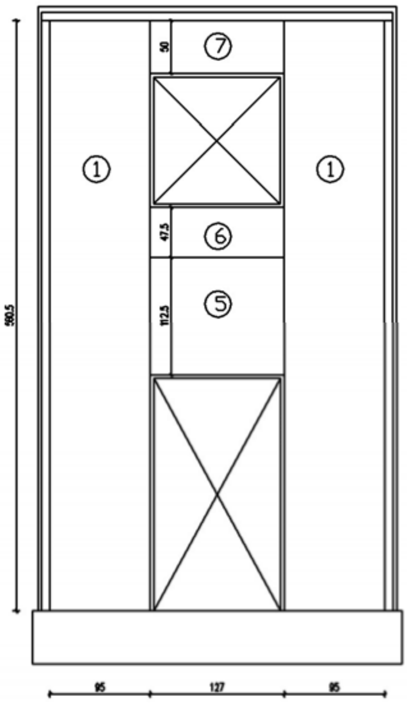
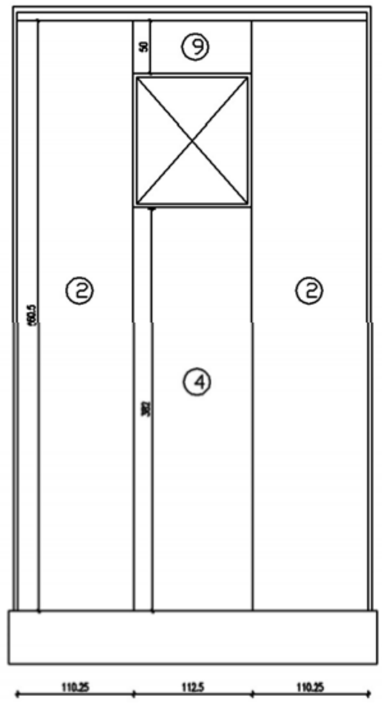

GROUND FLOOR PLAN
FIRST FLOOR PLAN
PROSPETTO C
PROSPETTO D
PROSPETTO B
PROSPETTO A
FIRST SLAB PLAN
FLAT ROOF PLAN

Figure 1b

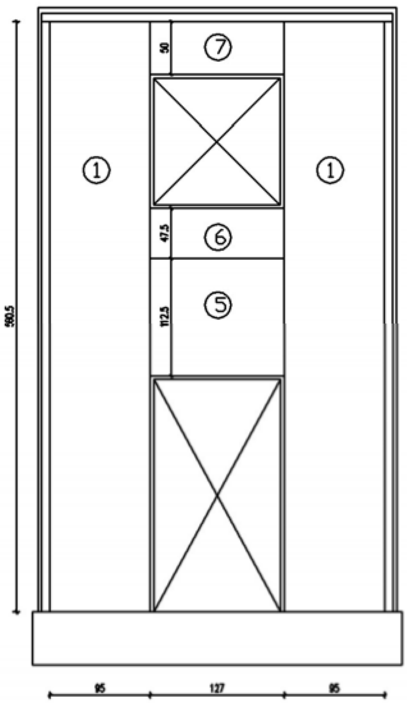
ELEVATION A



ELEVATION B



ELEVATION A



ELEVATION B

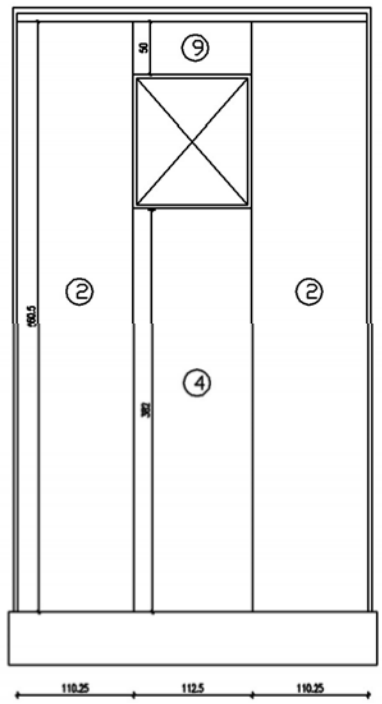


Figure 2

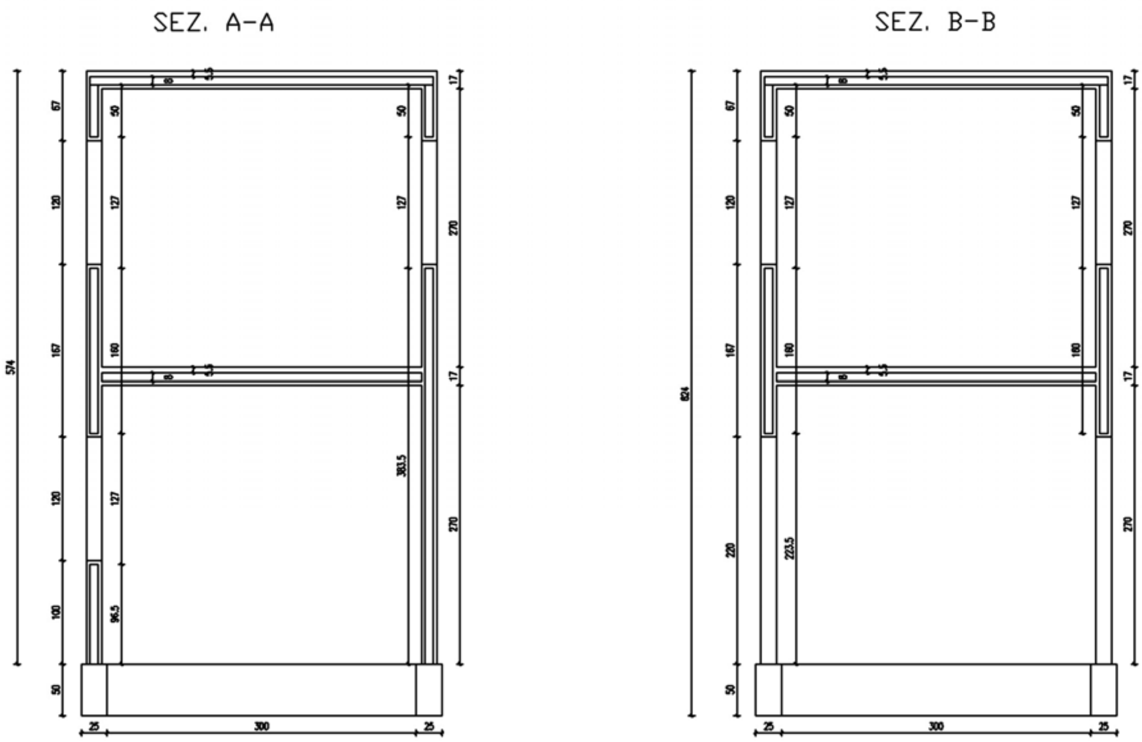


Figure 3

The model is embedded into base edging, made of reinforced concrete, closely attached to the table, with outer dimensions of 3.5*3.5 *m*, thickness 25 *cm* and height 50 *cm*, for an overall weight (calculated by ABAQUS, without bars and openings) of 37.00 *kN* (Figure 1).

The walls are built with panels with a total thickness of 15 *cm*, composed of an inner polystyrene layer which is 8 *cm* thick and two outer layers, each 3.5 *cm*, made of reinforced concrete with metal mesh; the overall weight is 1.60 kN/m^2.

The intermediate floors are composed of panels which are 17 *cm* thick, with a central polystyrene layer of 8 *cm* and two outer layers of reinforced concrete with metal mesh, the upper one 5.5 *cm* thick and the lower one 3.5 *cm* thick, with an overall weight of 2.10 kN/m^2.

The total mass of the model is approximately 14.0 $kN/(m/s^2)$.

The intermediate floor was subjected to an overload which simulates both the loads of the intermediate floor itself (equal to 2.60 kN/m2) and those acting on the flat roof (equal to 1.90 kN/m2) for a total of 43.50 kN. The decision to load only the intermediate floor was dictated by the need to keep the centre of the masses (which is found approximately 3.0 m above the level of the table) as low as possible, in order to limit the overturning moment on the table during the tests whilst still reaching high values of acceleration to the base and, therefore, high stresses on the first intermediate floor walls. The mass was kept constant throughout all the tests.

A numerical model with finite elements of the model described was perfected using the ABAQUS code, with 20-node cubic elements (Figures 4 and 5). The damping force assumed was 5%.

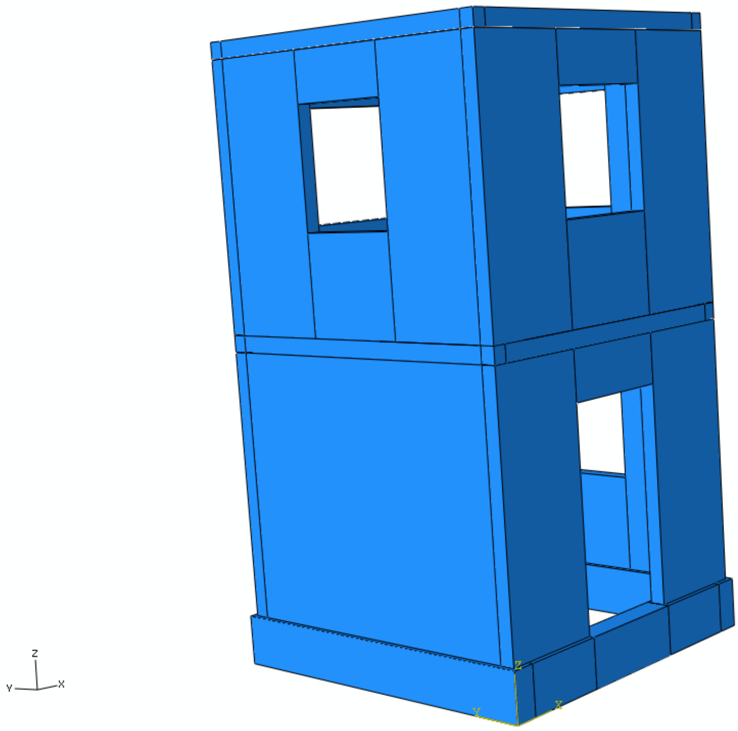


Figure 4

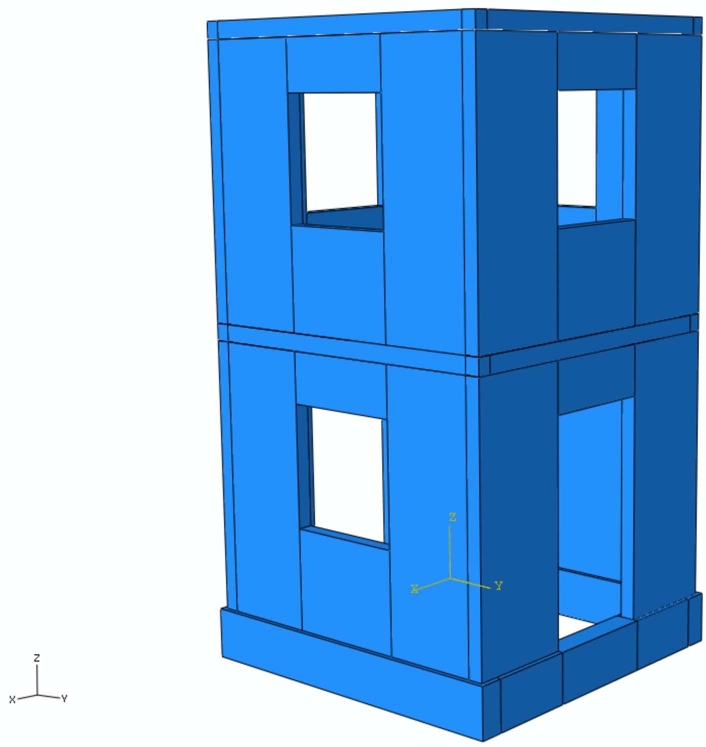


Figure 5

2.2 Equivalent modulus

A thickness equal to the total thickness, i.e. the sum of the various constituent layers, was assumed for both the walls and the intermediate floor (15 *cm* for the walls, 17 *cm* for the intermediate floors) while the material was attributed with a suitable equivalent elastic modulus.
For this purpose, the data of the compression and shear tests, conducted at EUCENTRE, on a wall without openings, was analysed. In particular, the 0.1% deformation test was taken into consideration, hypothesising linear behaviour (a probable hypothesis given the low level of deformation). From the force displacement curve graph, shown in Figure 6, a displacement of 2 *mm* can be read with a force value of 100 *kN*.
This test was simulated with ABAQUS, considering a panel with the dimensions 3.0*3.0 *m* and thickness 15 *cm*, embedded into the base and with the reinforced concrete edging pre-loaded with 150 *kN* on the top (Figure 7). The model was subjected to a horizontal load, distributed evenly at the top. The deformation obtained is shown in Figure 8.

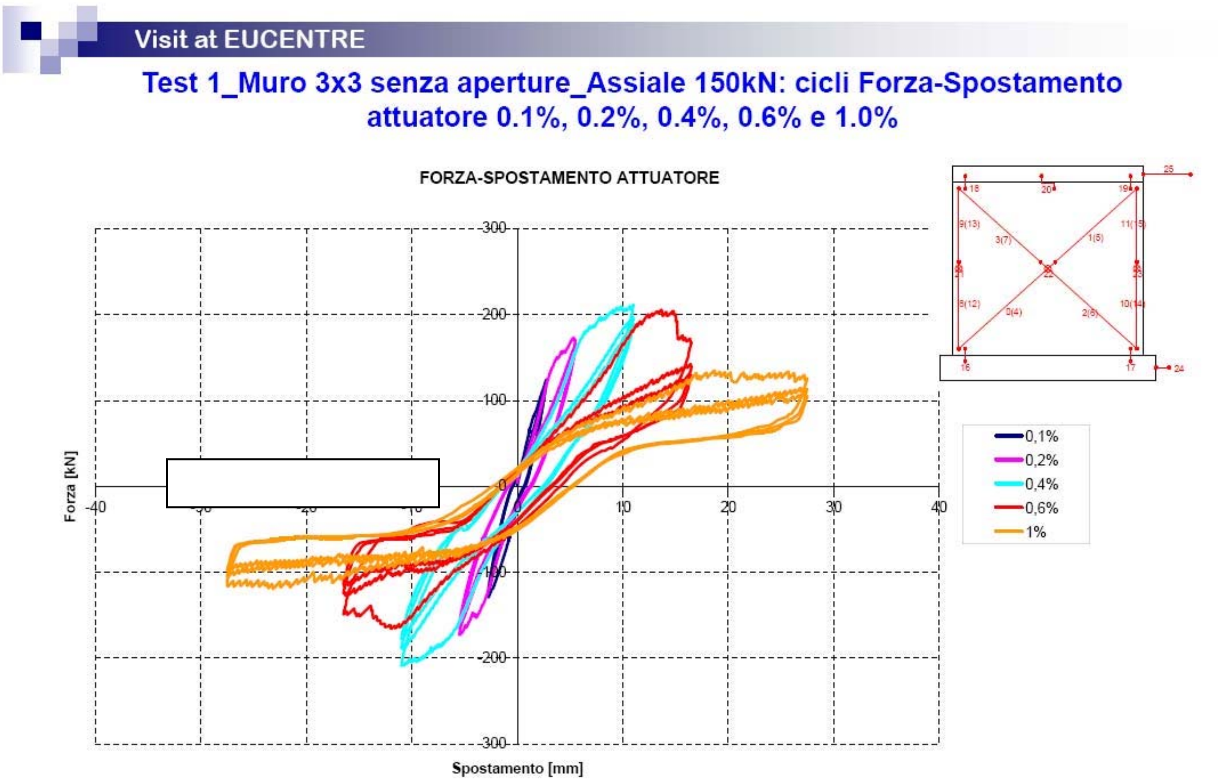


Figure 6 -TEST 1_ WALL 3X3 WITHOUT OPENINGS_AXIAL 150KN: ACTUATOR FORCE-DISPLACEMENT CYCLES

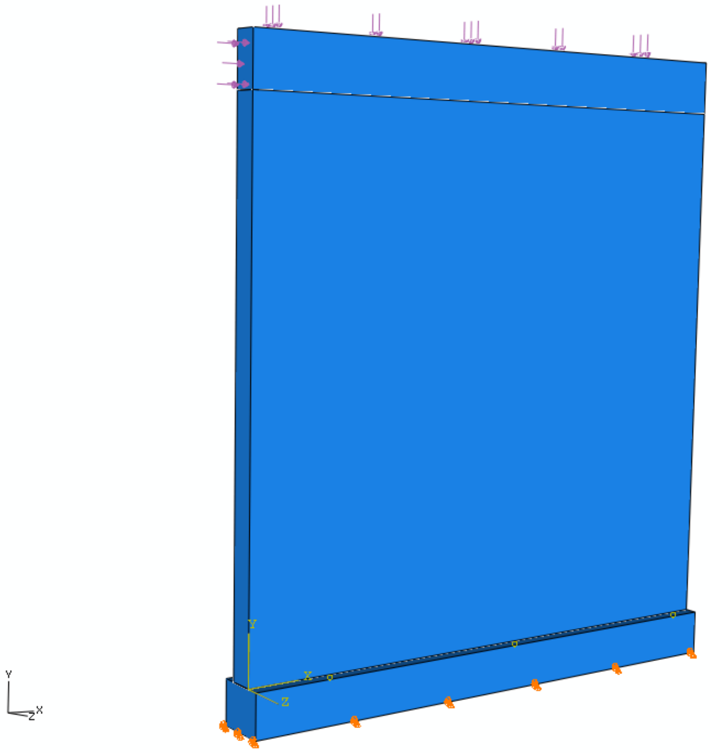


Figure 7

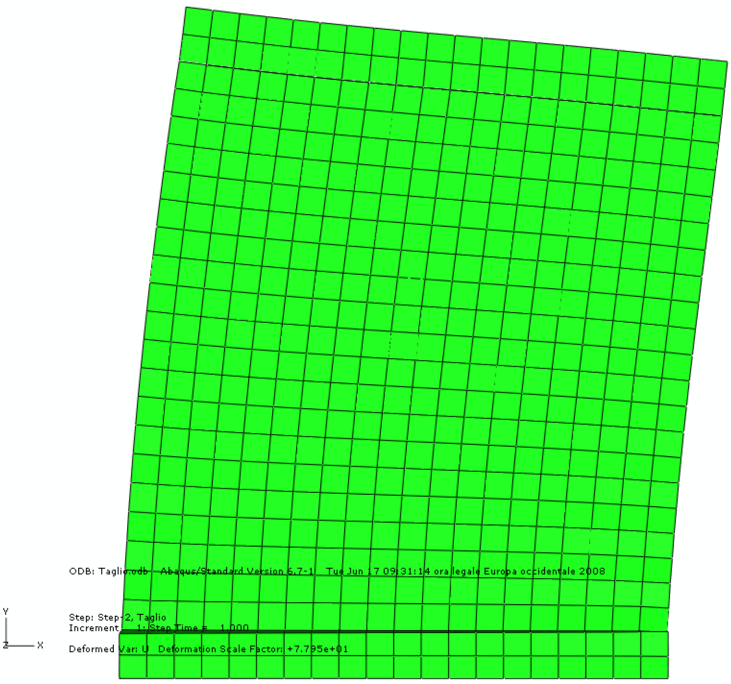


Figure 8

With Poisson's ratio set at ν = 0.2, the value of the *E* modulus was parameterised, in order to reproduce the linearised curve achieved in the tests. The optimum value, where there is good overlapping of the numerical curve with the experimental one, resulted as being equal to:

$$E = 2430 \quad MPa$$

This value is also confirmed by a theoretical calculation conducted on the hypotheses drawn up, disregarding the contribution of the reinforcement and schematising the wall as an embedded beam with a transversal force at the end.
From the expression of the deformation due to shearing:

$$\gamma = \chi \frac{T}{GA} = \frac{\otimes_T}{H}$$

where:

$\chi = 1.2$
$T = 100\ kN$
$G = E/2(1+\nu),\ \nu = 0.2$
$\gamma = arctg(2/3000)$,
$H = 300\ cm$
$A = L*b,\ b = 15\ cm,\ L = 300\ cm$

the following
displacement is obtained:

$$\otimes_T = \chi \cdot 2(1+\nu)\frac{T}{EA} \cdot H$$

The displacement due to bending is equal to:

$$\otimes_F = \frac{T \cdot H^3}{3EJ}$$

Since, in the experimental tests, the following was true:

$$\otimes_F + \otimes_T = 2 \quad mm$$

The result obtained is:

$$E = 2290 \quad \text{MPa}$$

An excellent match to the numerical simulation value.

As regards the intermediate floor, one of the tests conducted at the EUCENTRE in Pavia was reproduced on intermediate floors with similar characteristics to the mock-up one. The intermediate floor material was considered homogeneous and its characteristics were chosen to reproduce the experimental results in the best way possible. Elastoplastic behaviour with

$$E_{el} = 1800\ MPa \qquad E_{pl} = 900\ MPa \qquad \sigma_y = 0.2\ MPa$$

resulted as being the one which best matches the experimental results (Figure 11).

Figure 9 - Intermediate floor load test: green arrows: load, orange points: restraints

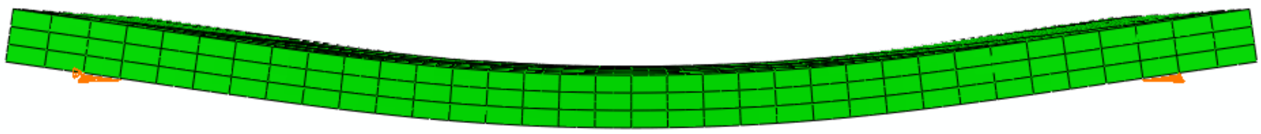


Figure 10 - Intermediate floor load test - deformed

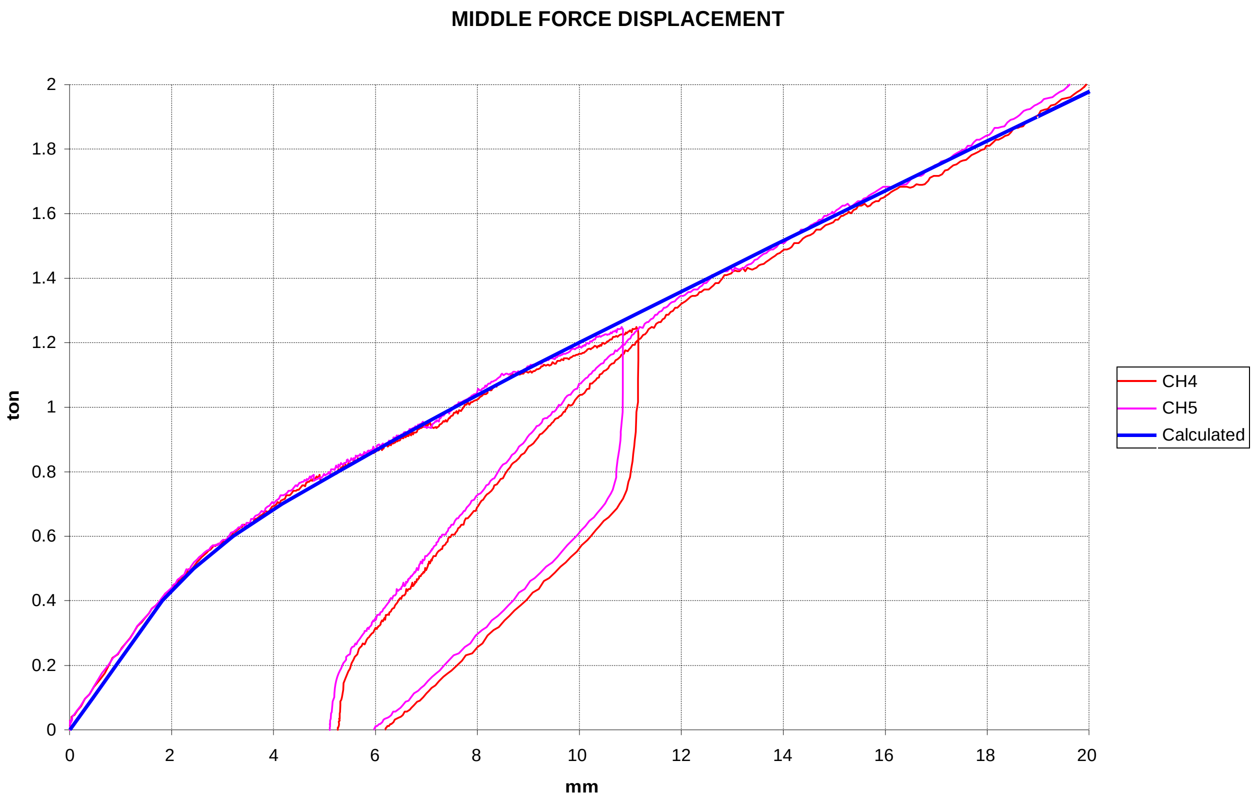
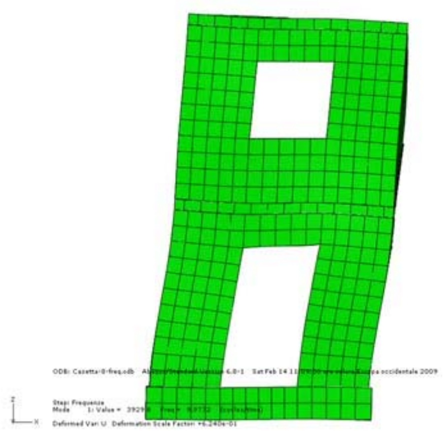


Figure 11– Comparison of experimental data – Homogeneous elastoplastic material theoretical model

With these elastic modulus values of the walls and intermediate floors respectively, the modulus analysis was conducted, and provided the values of the first 30 resonance frequencies. In the first two vibration modes, associated with the frequency values of 10.0 and 12.0 *Hz* respectively, a large part of the mass is activated, with bending of the whole structure (Figure 12). The third and fifth modes concern the out-of-plane vibration of the intermediate floors (Figure 13), while the fourth mode is torsional.


Mode 1

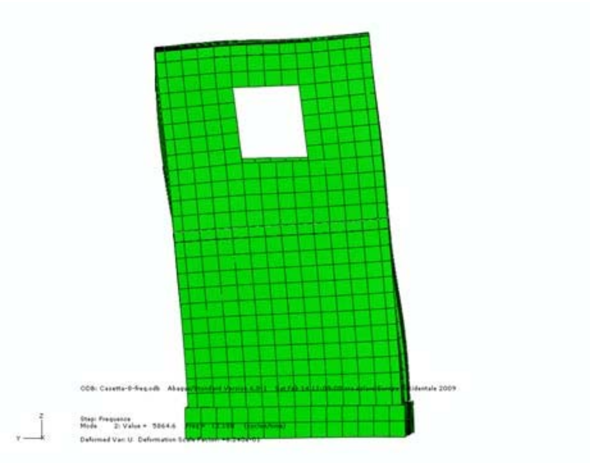
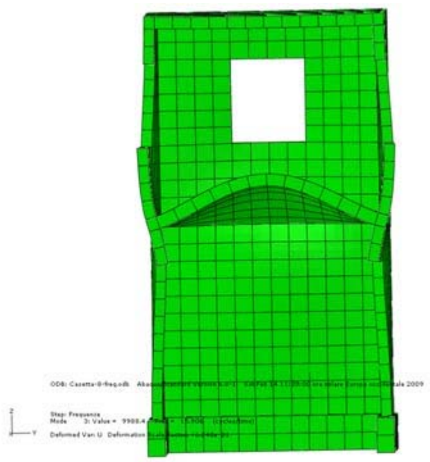

Mode 2

Figure 12


Mode 3

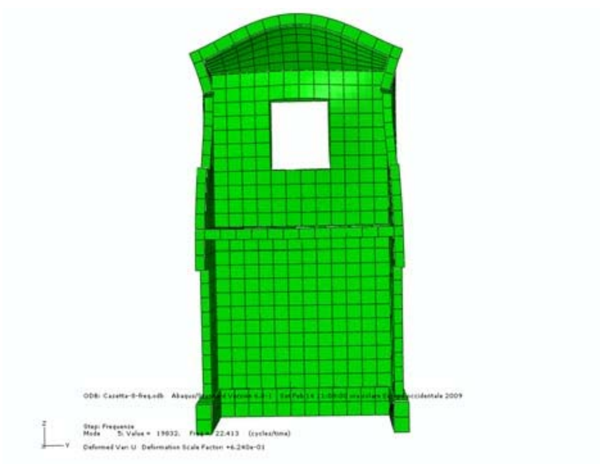

Mode 5

Figure 13

2.3 Results

TOTAL MASS OF MODEL = 22189 kg
LOCATION OF THE CENTRE OF MASS OF THE MODEL (m)
X = 1.73 Y = 1.75 Z = 3.09

Table 1. Eigenvalues

MODE No	EIGENVALUE	FREQUENCY (rad/s)	FREQUENCY (Hz)	GENERALIZED MASS
1	3929.8	62.688	9.9772	9320.8
2	5864.6	76.581	12.188	5894.3
3	9988.4	99.942	15.906	1293.4
4	17541.	132.44	21.079	5838.1
5	19832.	140.83	22.413	553.05
6	28356.	168.39	26.801	5614.7
7	35690.	188.92	30.067	2060.4
8	35803.	189.22	30.115	1112.1
9	38155.	195.33	31.088	2260.9
10	41202.	202.98	32.306	623.51
11	51754.	227.50	36.207	633.88
12	60561.	246.09	39.167	586.37
13	64021.	253.02	40.270	624.62
14	65449.	255.83	40.717	672.63
15	72818.	269.85	42.948	656.31
16	77350.	278.12	44.264	228.05
17	82664.	287.51	45.759	216.85
18	87486.	295.78	47.075	1471.5
19	89703.	299.51	47.668	1036.2
20	90159.	300.27	47.789	821.44
21	98435.	313.74	49.934	680.83
22	99606.	315.60	50.230	168.46
23	103536	321.77	51.211	1572.5
24	110671	332.67	52.946	217.31
25	124998	353.55	56.269	1557.8
26	130036	360.60	57.392	494.61
27	130324	361.00	57.456	958.61
28	133823	365.82	58.222	473.71
29	135703	368.38	58.629	423.27
30	151887	389.73	62.027	251.14

Table 2 Participating masses

Mode No.	X-COMP.	Y-COMP.	Z-COMP.	X-ROTATION	Y-ROTATION	Z-ROTATION
1	16154.	3.40760E-11	3.4122	10.450	3.02039E+05	49472.
2	5.16092E-11	14165.	3.25744E-11	3.00958E+05	1.87259E-09	56697.
3	6.3744	8.26659E-11	4267.4	13069.	11769.	19.522
4	1.42104E-10	105.94	1.17122E-11	6843.2	2.62195E-09	35655.
5	1.8934	6.18297E-11	2366.8	7248.4	7396.2	5.7986
6	993.09	2.87540E-14	0.57054	1.7473	6099.7	3041.3
7	1.72611E-09	1359.9	3.30750E-12	16.434	6.30499E-08	1225.0
8	55.130	4.83084E-08	1.1256	3.4473	2029.9	168.84
9	1.96808E-11	1139.2	1.76282E-11	1622.8	6.38318E-10	1721.8
10	5.3439	2.90105E-10	0.82228	2.5181	83.699	16.366
11	15.861	1.77973E-11	0.99663	3.0522	28.308	48.573
12	99.804	3.09230E-12	19.152	58.652	140.05	305.65
13	6.50180E-11	83.624	3.27019E-10	2.5113	1.47484E-09	166.55
14	40.180	9.60289E-11	10.440	31.974	456.96	123.05
15	3.3365	5.78281E-11	1719.3	5265.5	4804.7	10.218
16	6.70638E-10	8.6221	7.86035E-10	2.8359	2.83269E-09	1177.0
17	5.04609E-11	52.484	1.39051E-09	24.705	1.99063E-09	1.5392

18	0.29903	9.43637E-11	7117.7	21798.	22796.	0.91577
19	1.69422E-11	20.766	2.29204E-08	331.84	9.59888E-08	26.980
20	2.4228	6.83139E-11	486.76	1490.7	182.20	7.4199
21	4.87852E-10	1.5837	1.10198E-08	11.933	1.78740E-08	50.634
22	3.4056	1.82438E-10	310.73	951.61	791.12	10.430
23	1.15302E-11	6.4066	4.06748E-12	26.341	1.27559E-10	8.0457
24	110.04	6.73353E-12	164.65	504.25	357.63	337.01
25	9.42702E-11	4.9719	4.00574E-11	2.8352	5.45987E-10	325.92
26	3.60555E-11	0.31695	3.19711E-09	12.218	3.39204E-09	253.11
27	0.13151	5.28507E-10	1.4191	4.3466	1.8296	0.40347
28	7.40128E-10	8.1019	2.98302E-12	10.148	1.28288E-11	83.229
29	4.6409	5.97438E-10	0.44632	1.3668	17.227	14.212
30	1.01027E-11	13.260	1.81896E-10	98.726	3.53536E-10	504.06
TOT.	17496	16970	16472	3.60409E+05	3.58994E+05	1.51478E+05

2.4 Comparison with experimental data

An initial comparison with the experimental data to check whether the model is able to reproduce the behaviour of structures built with the EMMEDUE system was made by comparing the response in terms of the accelerations recorded at flat roof level in the *Tolmezzo* test *0.25g*, in both direction X and direction Y (note that the X and Y axes are inverted between the test and the code). The results, shown in the figures below, show a good match.

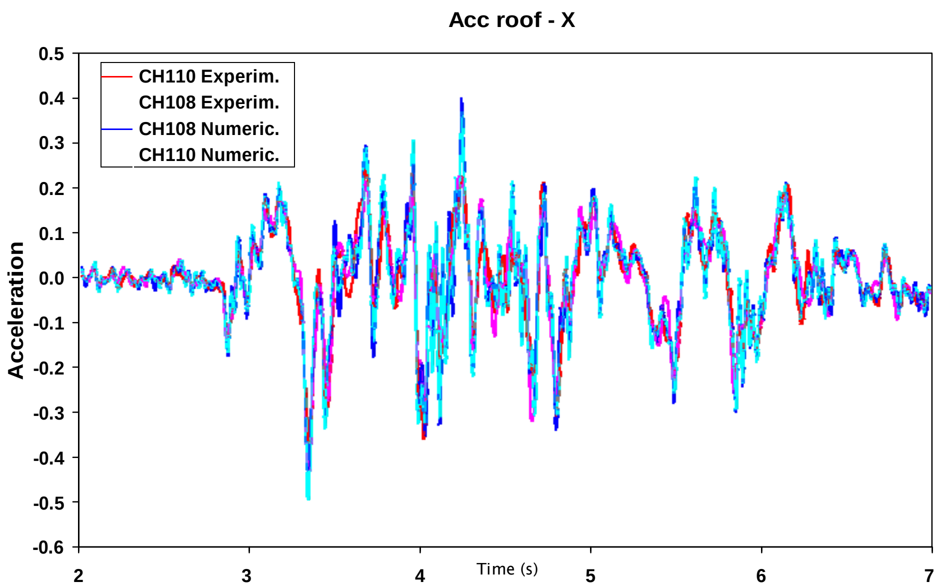


Figure 14

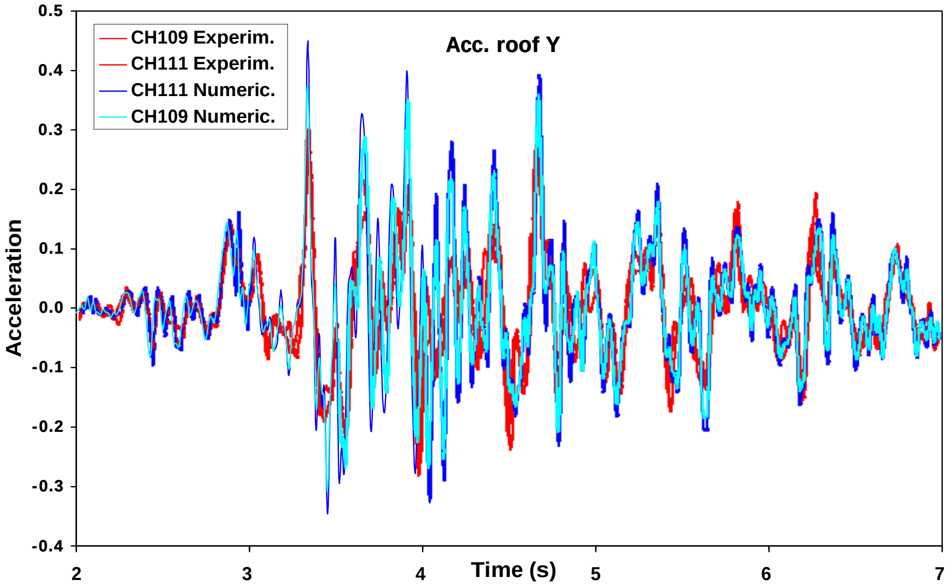

Acc. roof Y
CH109 Experim.
CH111 Experim.
CH111 Numeric.
CH109 Numeric.
Acceleration
Time (s)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
2
3
4
5
6
7

Figure 15

3 H MODEL

With the H model, the intention is to check seismic behaviour of the wall-wall node and the node between the intermediate floor and the wall. The geometric data is shown in figure 16, the finite element model is shown in figure 17. A mass simulating both the loads of the first intermediate floor (260 *kg/m*^{2}) and those acting on the second intermediate floor (190 *kg/m*^{2}) is placed on the intermediate floor element.
The H model been subjected to a time history in the longitudinal direction, a peak acceleration value such that it reaches the maximum overturning moment permitted by the vibrating table. The damping force assumed was 5%.

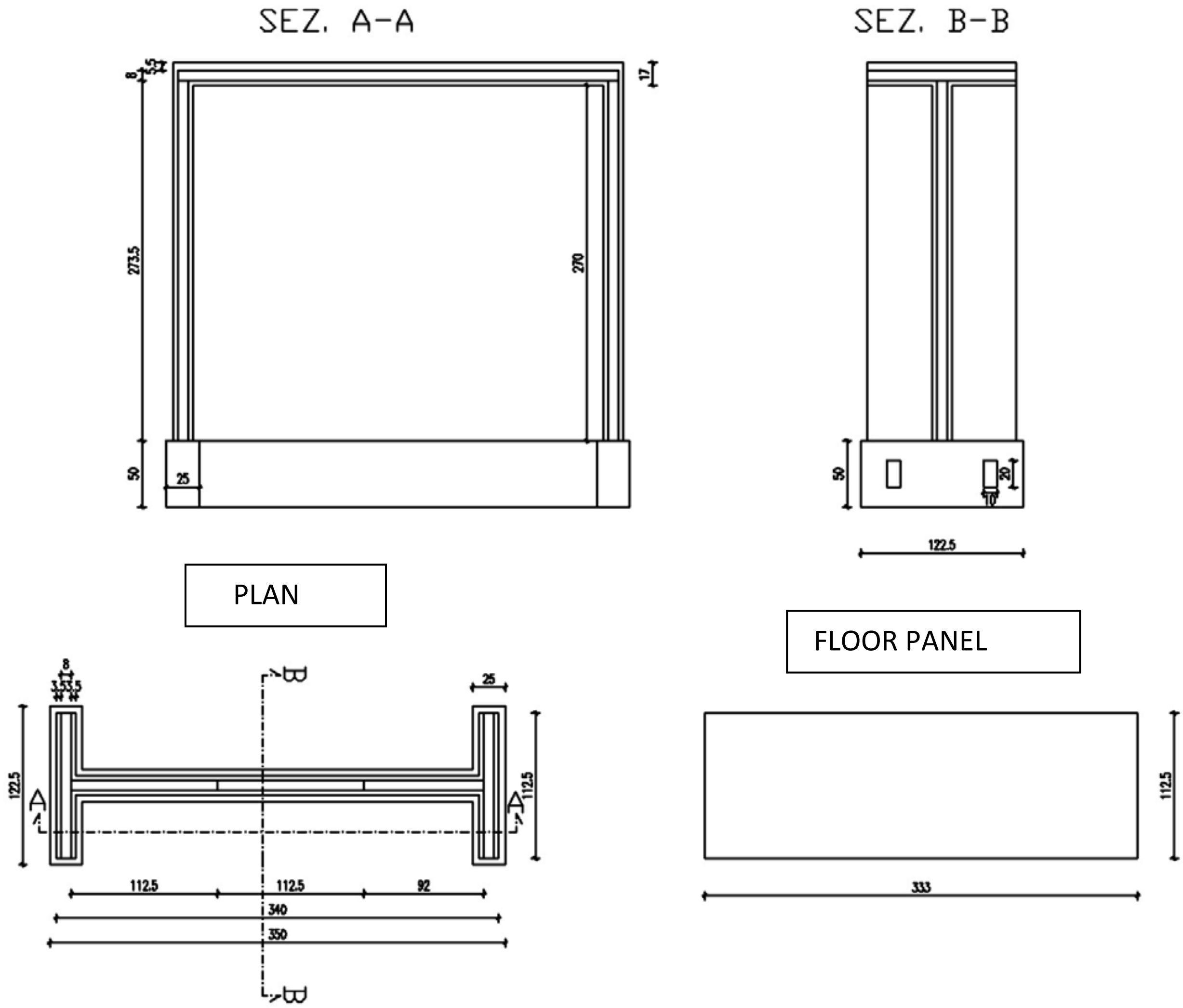


Figure 16

3.1 Results

TOTAL MASS OF MODEL = 6918 kg

LOCATION OF THE CENTRE OF MASS OF THE MODEL (m)
X = 1.75   Y = 0.0   Z = 2.06

The maximum overturning moment for the table is reached with PGA = 1.0 *g*. The amplification in terms of acceleration from the base to the intermediate floor is equal to 1.6; the edging-intermediate floor drift is less than 1.0 *mm*.

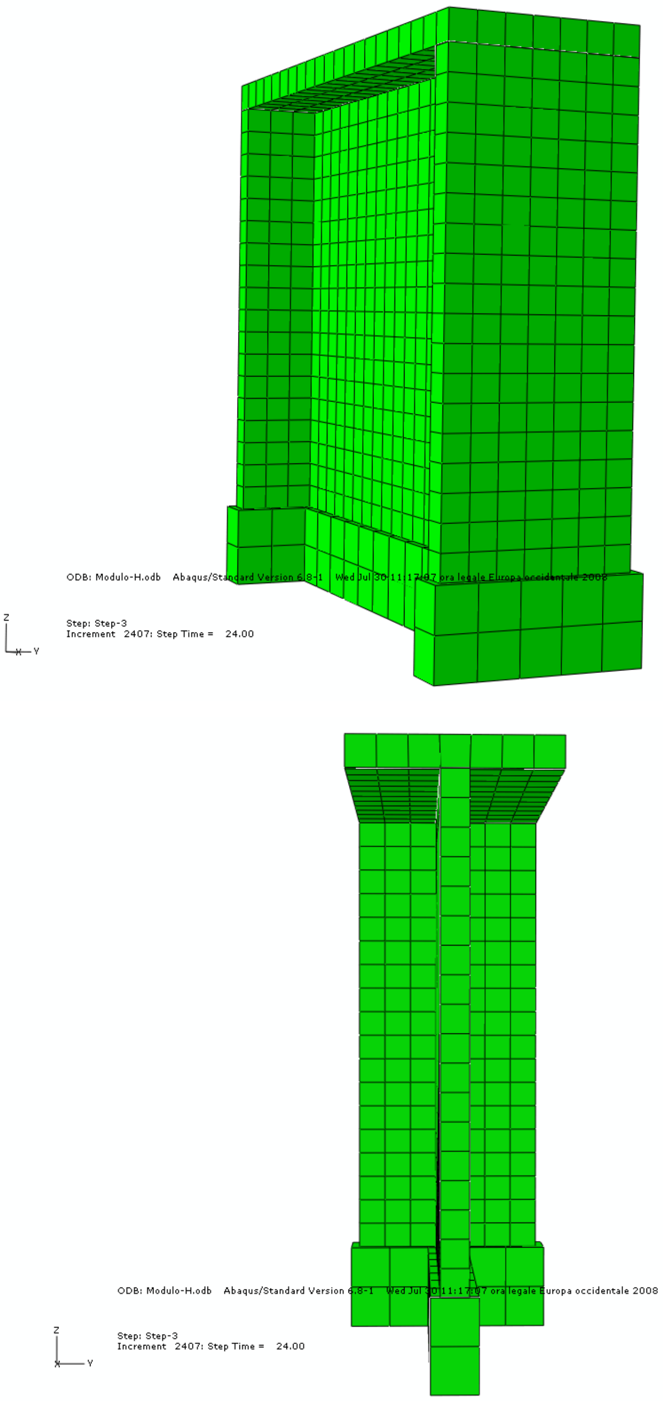


Figure 17 H model
cross section

Table 3 Eigenvalues

Mode No.	EIGENVALUE	FREQUENCY (rad/s)	FREQUENCY (Hz)	GENERALIZED MASS
1	2748.3	52.424	8.3436	2915.5
2	7337.2	85.657	13.633	1343.1
3	26506.	162.81	25.912	694.53
4	31059.	176.23	28.049	3455.1
5	63747.	252.48	40.184	541.25
6	84834.	291.26	46.356	1908.6
7	94528.	307.45	48.933	670.28
8	96865.	311.23	49.534	593.93
9	1.26504E+05	355.67	56.607	453.93
10	1.61538E+05	401.92	63.967	528.62
11	2.03015E+05	450.57	71.711	239.16
12	2.15062E+05	463.75	73.808	737.31
13	2.55147E+05	505.12	80.393	413.13
14	2.56917E+05	506.87	80.671	581.48
15	3.01409E+05	549.01	87.377	332.33
16	3.66565E+05	605.45	96.360	410.32
17	3.70221E+05	608.46	96.839	794.24
18	3.76158E+05	613.32	97.612	1137.5
19	3.97895E+05	630.79	100.39	875.12
20	4.13499E+05	643.04	102.34	1602.9

Table 4 Participating masses

MODE NO	X-COMPONENT	Y-COMPONENT	Z-COMPONENT	X-ROTATION	Y-ROTATION	Z-ROTATION
1	9.61397E-24	4048.8	7.18323E-14	39739.	2.19971E-13	12400.
2	2.47407E-13	3.62955E-13	8.90802E-21	2.92883E-12	1.91130E-12	5081.5
3	2.87435E-18	265.48	3.32132E-12	326.65	1.02103E-11	813.03
4	4299.8	1.96909E-19	7.26620E-14	2.24922E-19	44760.	4.89921E-15
5	1.27150E-19	28.270	1.52749E-11	0.38813	4.67711E-11	86.577
6	2.12556E-21	170.35	1.80572E-11	374.42	5.53026E-11	521.70
7	4.05762E-13	1.03221E-17	1.02873E-15	1.97009E-15	1.27604E-12	277.32
8	8.55912E-15	1.60473E-12	2923.5	1.84412E-12	8953.2	4.86744E-12
9	1.05318E-12	1.43249E-13	2.11199E-17	2.23002E-13	3.33293E-12	2.9058
10	92.295	4.30712E-18	4.07950E-14	6.33540E-18	434.44	1.00422E-12
11	8.79877E-18	20.122	3.00394E-12	23.390	9.23251E-12	61.622
12	1.04487E-17	98.414	1.09022E-11	124.25	3.34569E-11	301.39
13	2.12457E-13	5.60593E-12	700.92	6.27398E-12	2146.6	1.63843E-11
14	4.52894E-13	1.14375E-13	1.00558E-14	1.44269E-13	4.32815E-13	621.83
15	5.65591E-18	55.795	4.60011E-13	28.954	1.41694E-12	170.87
16	6.99664E-11	3.12326E-11	2.80407E-19	3.38073E-11	3.80731E-11	0.87497
17	341.13	1.28543E-15	3.27785E-12	1.29463E-15	167.11	3.64015E-13
18	1.23130E-15	227.04	6.83219E-12	240.68	2.11210E-11	695.30
19	1.19465E-11	3.04315E-12	1.24832E-16	3.11316E-12	1.59138E-13	97.036
20	3.89023E-13	6.07356E-13	3.8823	5.82612E-13	11.889	1.82955E-12
TOT.	4733.2	4914.3	3628.3	40858.	56473.	21131.

4 C MODEL

With the C model, the intention is to check seismic behaviour of the wall-wall angle node and the angle node between the intermediate floor and the wall. The geometric data is shown in figure 18; the finite element model is shown in figure 19. As with the H model, a mass simulating both the overloads acting on the intermediate floor itself (260 *kg/m*^{2}) and those acting on any flat roof (190 *kg/m*^{2}) is placed on the intermediate floor.
The C model has been subjected to a time history in the longitudinal direction, with a peak acceleration value such that it reaches the maximum overturning moment permitted by the vibrating table. The damping force assumed was 5%.

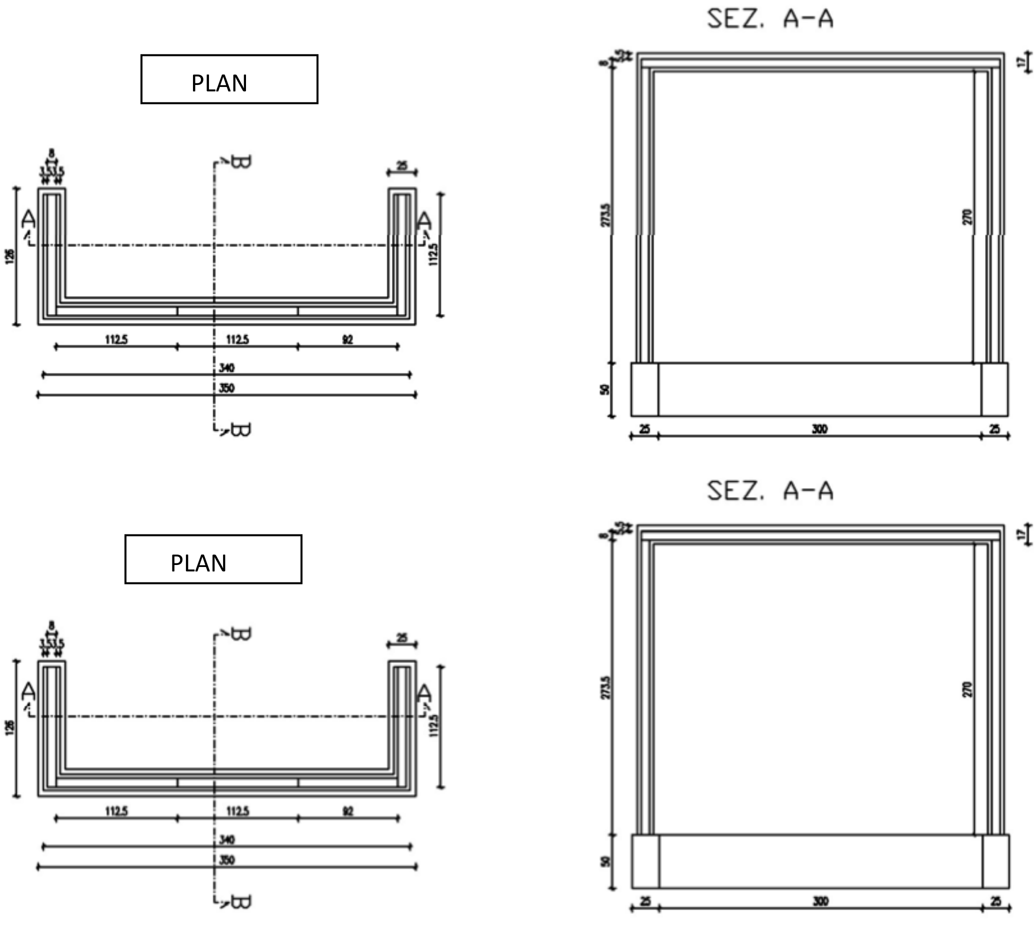
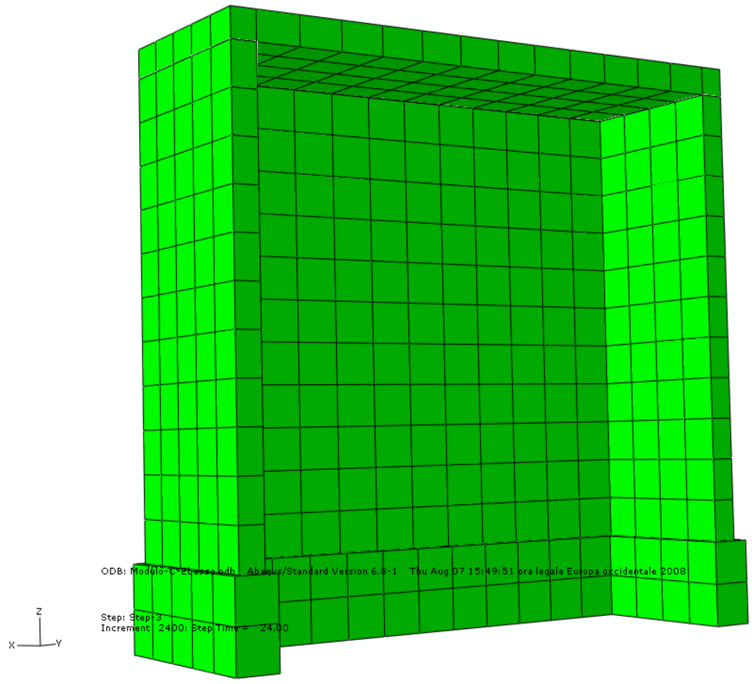


Figure 18

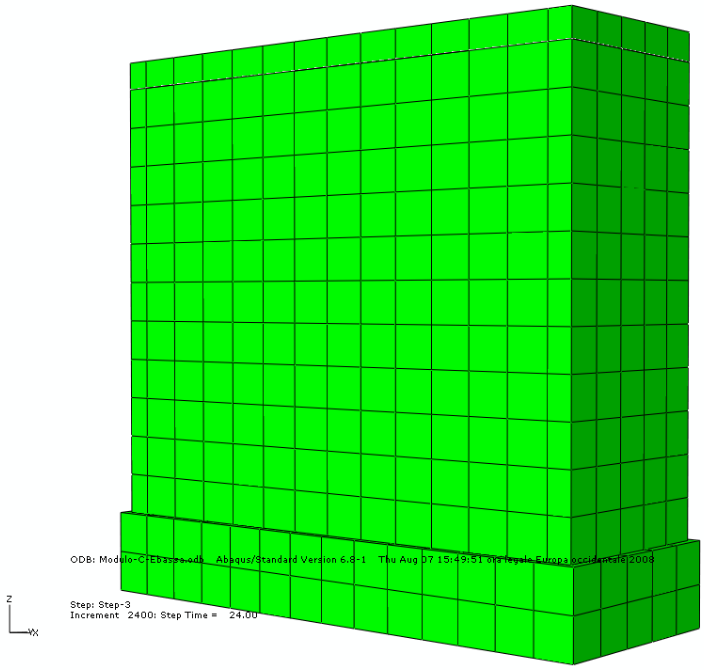
4.1 Results

TOTAL MASS OF MODEL = 7059 kg
LOCATION OF THE CENTRE OF MASS OF THE MODEL (m)
X = 1.75 Y = 0.46 Z = 2.07

The maximum overturning moment for the table is reached with PGA = 1.0 *g*. The amplification in terms of acceleration from the base to the intermediate floor is equal to 2.1; the edging-intermediate floor drift is approximately 2.0 *mm*.



C model view 1



C model view 2

Figure 19

Table 5 Eigenvalues

MODE No.	EIGENVALUE	FREQUENCY (ra	FREQUENCY (Hz)	GENERALIZED MASS
1	4561.8	67.	10.750	2925.4
2	6634.4	81.	12.963	2568.0
3	10325.	10	16.172	427.83
4	34985.	18	29.769	754.02
5	44012.	20	33.389	488.19
6	48677.	22	35.114	1127.9
7	68416.	26	41.629	171.30
8	73797.	27	43.235	221.59
9	1.11748E+05	33	53.203	698.67
10	1.29096E+05	35	57.184	775.70
11	1.64294E+05	40	64.511	416.29
12	1.76843E+05	42	66.929	715.99
13	2.43889E+05	49	78.599	631.81
14	2.72923E+05	52	83.146	450.76
15	2.86876E+05	53	85.245	694.18
16	2.99441E+05	54	87.092	231.93
17	3.24755E+05	56	90.698	342.34
18	3.56494E+05	59	95.027	1166.6
19	3.81820E+05	61	98.344	1121.8
20	3.86060E+05	62	98.889	830.86

Table 6 Participating masses

MODE No.	X-COMP.	Y-COMP.	Z-COMP.	X-ROTATION	Y-ROTATION	Z-ROTATION
1	3.17356E-10	3869.1	132.65	41329.	406.23	11849.
2	1846.7	8.07381E-10	8.78753E-11	9.13284E-09	17272.	6230.4
3	2.24363E-11	440.41	1347.3	775.50	4126.2	1348.8
4	1140.3	1.53709E-12	1.10779E-13	7.10097E-11	16131.	10.739
5	2.71545E-11	92.654	18.632	24.059	57.061	283.75
6	1490.1	1.41298E-11	9.26925E-13	7.29717E-11	11034.	575.05
7	6.32628E-02	1.78873E-09	1.55675E-12	2.03703E-09	1240.9	58.114
8	1.78130E-11	121.30	3.6646	163.53	11.222	371.47
9	4.43404E-12	13.531	259.76	316.22	795.53	41.438
10	2.42158E-13	95.575	254.93	142.59	780.73	292.70
11	35.003	1.86338E-12	6.34163E-13	5.64453E-12	104.88	441.12
12	6.28966E-15	66.889	758.41	263.02	2322.6	204.85
13	111.27	3.48373E-11	4.63027E-13	4.17626E-11	66.901	5.7162
14	2.31948E-11	7.2947	604.95	48.794	1852.6	22.340
15	6.5984	1.71262E-09	6.44950E-09	2.13480E-10	512.06	11.536
16	5.01815E-10	76.580	119.87	28.502	367.09	234.52
17	61.567	1.33184E-09	3.30590E-10	1.02250E-09	194.58	115.38
18	1.93650E-11	148.79	116.64	45.979	357.20	455.68
19	12.513	2.93944E-10	1.32293E-08	4.47397E-09	0.10952	452.06
20	7.56961E-10	17.296	557.18	195.16	1706.4	52.966
TOT	4704.2	4949.4	4174.0	43333.	59339.	23058.