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Eccomas Proceedia COMPDYN (2017) 849-865

ECCOMAS
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COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

FUSEIS PIN LINKS: INFORMATION BROCHURES AND DESIGN OF CASE STUDY

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Keywords: Anti-seismic system, information documents, code-approval, methodological procedure, pre-normative documents, case studies, application examples, seminars, INNOSEIS

Abstract. *In the frame of the INNOSEIS research project, which is funded by RFCS, information documents for INERD-pin and FUSEIS-pin links have been produced by NTUA for dissemination to all partners of the construction sector such as architects, structural engineers, construction companies, steel producers and all potential decision makers of the construction sector. For each of the two systems, an approximately 40-page information brochure has been drafted in English. They contain a description of the main features of the system, overall dimensions, preferred structural materials, range of sizes, member shapes, typical cross sections and limitations, possible arrangements for conceptual design, recommended structural details etc. and indicative application examples of selected building structures. In addition, information is given regarding the non-linear force-deformation characteristics and ductility/strength capacities of the systems, the hysteretic behavior of elements under cyclic loading, including rules for stiffness and strength degradation. Finally, pre-normative q-factors are proposed and reference is made to application examples in design practice, previous publications and literature.*

Case studies on the seismic design of steel buildings incorporating the systems are presented. FUSEIS pin links have been applied on a 2-storey and on a 4-storey office steel building while INERD pin connections have been applied in an existing 6-storey commercial reinforced concrete building. Each case study refers to the conceptual design, loads and load combinations, modelling, analysis, detailed design and structural detailing. Design follows the provisions of the Eurocodes and the pre-normative guidelines that were developed within the project. The existing building was designed according to an outdated national seismic code. It does not comply with the requirements of EN 1998-1, hence the need for upgrading.

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5461.18032

1 INTRODUCTION

In the frame of the INNOSEIS research project, which is funded by RFCS, information brochures have been produced for 12 innovative systems, in order to disseminate to all partners of the construction sector such as architects, structural engineers, construction companies, steel producers and all potential decision makers of the construction sector. NTUA was responsible for the production of the information documents for INERD pin connections and FUSEIS pin links. For each system, an approximately 40-page information brochure has been drafted in English. They contain a description of the main features of the system, overall dimensions, preferred structural materials, range of sizes, member shapes, typical cross sections and limitations, possible arrangements for conceptual design, recommended structural details etc. and indicative application examples of selected building structures. In addition, information is given regarding the non-linear force-deformation characteristics and ductility/strength capacities of the systems, the hysteretic behavior of elements under cyclic loading, including rules for stiffness and strength degradation. Finally, pre-normative q-factors are proposed and reference is made to application examples in design practice, previous publications and literature.

In addition, case studies on the seismic design of steel buildings incorporating the innovative systems have been prepared. FUSEIS pin link has been applied on a 2-storey and on a 4-storey office steel building and INERD pin connection has been applied on an existing 6-storey commercial reinforced concrete building. Each case study refers to the conceptual design, loads and load combinations, modelling, analysis, detailed design and structural detailing. The design follows the provisions of the Eurocodes and the pre-normative design guidelines that were developed within the project. The existing building is designed according to an outdated national seismic code. It does not comply with the requirements of EN 1998-1, hence the need for upgrading.

In the current document, only the FUSEIS pin links brochure is presented, as the general structure and format of the documents are identical. Similarly, only the case study of the 4-storey building with the FUSEIS pin link systems is described.

2 INFORMATION BROCHURES

2.1 General

As mentioned before, information brochures for FUSEIS pin links and INERD pin connection have been produced by NTUA and are readily available on the INNOSEIS project website (http://innoseis.ntua.gr), under the tab “Deliverables”. Below, the general structure of the documents is outlined:

a) Description of the main features of system
b) Experimental results
c) Design rules
d) Analyses on 2D building frames
e) Conclusions
f) Field of application
g) Publications
h) Bibliographic references

In the following chapters, the contents of the FUSEIS pin link brochure are briefly presented.

2.2 Description of FUSEIS pin link system

The FUSEIS pin links system consists of a pair of strong columns connected by multiple horizontal links (Fig. 1). The horizontal links can be designed in two different ways. In the first, each link includes two receptacle beams connected through a short steel pin (Fig. 2a). In the second, in order to avoid the application of receptacles, the pins are directly bolted to end-plates which are connected to the column flanges (Fig 2b). Pin section is reduced in the middle part of the pin to promote damage away from the connection area. Pins detailed in such a way require less effort in fabrication and erection without a change in their response.

Under strong lateral forces, the pins will dissipate a large amount of energy, leaving the rest of the structure undamaged. Repair works are easy, since they are restricted to the pins which are not generally subjected to vertical loads, as they are placed between floor levels.

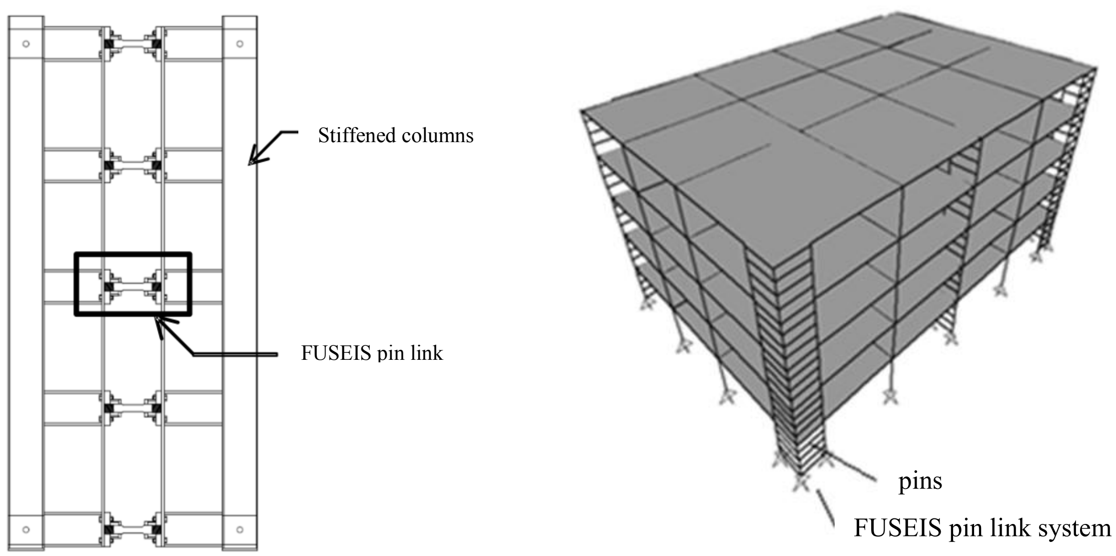


Figure 1: FUSEIS pin link system configuration and position in a building

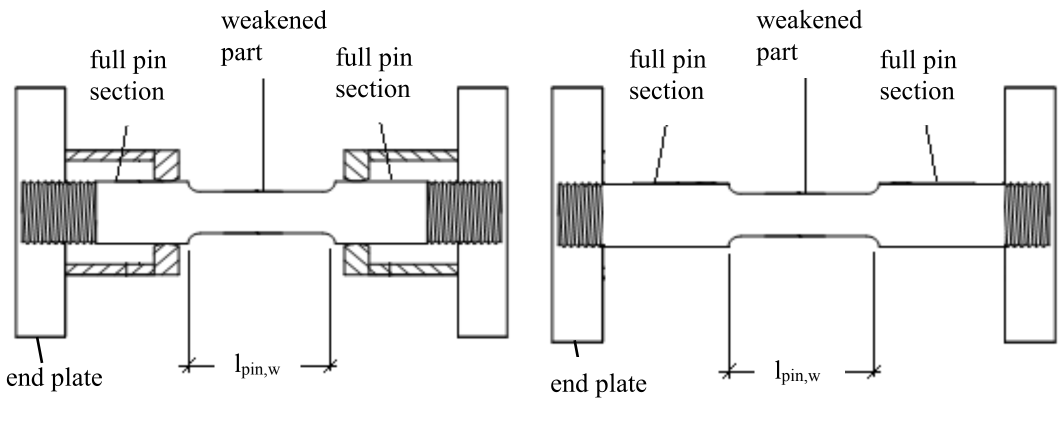


Figure 2: FUSEIS pin link a) with receptacles, b) without receptacles

Experimental investigations showed that the system resists lateral loads as a vertical Vierendeel beam, where the main actions in pins are bending and shear while in columns are bending and axial (Fig. 3). Considering hinges at the midpoints of pins and columns, the internal moments and forces for horizontal loading in the elastic state may be derived from statics.

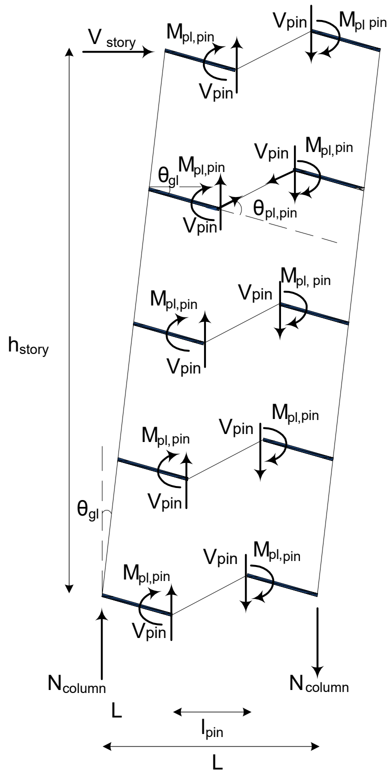


Figure 3: Static system and theoretical internal forces

2.3 Experimental investigations on FUSEIS pin links

2.3.1. Experimental investigations on individual links

In total eight test were conducted on pin links, two under monotonic and six under cyclic loading. The specimens tested consisted of a 400mm circular pin weakened in the middle and two receptacle beams SHS120x10. The pin was divided to three parts. The diameter at the ends was Φ60 and in the middle part the diameter was reduced to Φ45mm (Fig. 4). The length of the weakened part was such, to ensure the development of a bending mechanism.

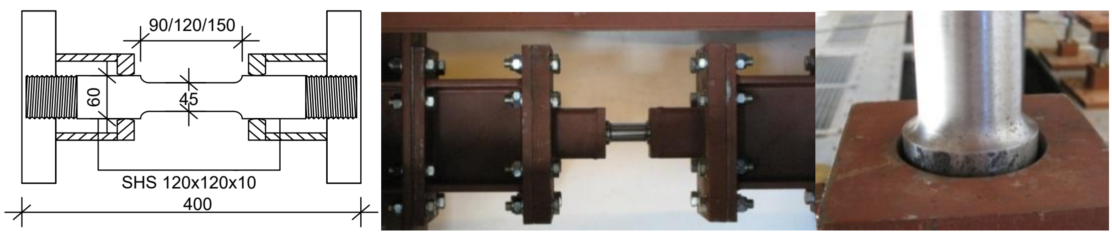
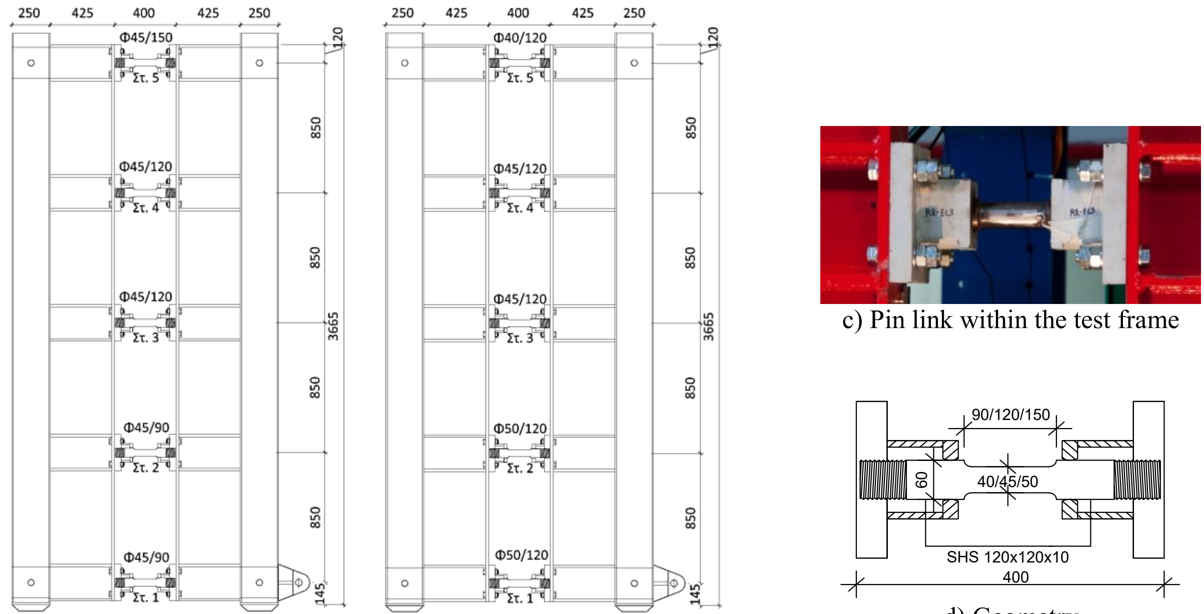


Figure 4: Fabricated pin links specimens before testing

2.3.2. Experimental investigations on full scale frames

Two full scale tests on frames with FUSEIS pin links were conducted at the Institute of Steel Structures of NTUA. The experimental setup included a resistance space frame test rig, a computer-controlled hydraulic cylinder and the test frame. The test frame consisted of two strong columns rigidly connected to five pin links. The height of the frame was 3.40 m and the axial distance of the columns L=1.50 m. The columns of the test frame were pin - jointed at the top and bottom connections, while their inner sides were stiffened by T-sections to remain elastic (Fig. 5).

Similar to the tests on individual pin links, the fuses consisted of a 400 mm pin and two SHS beams as receptacles. The geometry of the weakened part of the pin was selected to ensure the development of bending mechanisms. Test M4 included pins with the same diameter (Φ45) and three different lengths of the weakened part (l_{pin}=90, 120, 150 mm > 39 mm), and test M5 pins with different diameters (Φ40, 45, 50) and the same length of the weakened part (l_{pin}=120 mm > 43.4 mm).



a) M4
b) M5
c) Pin link within the test frame
d) Geometry

Figure 5: a), b) Test frames c), d) Specimen

2.4 Design rules

The conclusions from the analytical and numerical studies were summarized in a design guide for practical application. The design guide gives recommendations on the selection of the appropriate links as a function of the most important parameters, like frame configuration, seismic zone, spectrum, and more generally the strength and deformation demand. The design methodology, described in the design guide, is based on the provisions of EN 1993-1-1 and EN 1998-1-1. Some clauses of EN 1998-1-1 were appropriately rearranged to cover the use of the system by the normal Code provisions. It also includes structural details and constructional measures.

2.4.1. Preliminary design

As previously mentioned, the FUSEIS pin link system works as a vertical Vierendeel beam. Considering that the «FUSEIS pin link» resists alone the lateral loads of the structure, a rough estimation of the required number of FUSEIS systems for a building in each direction and the type of their cross sections can be made from the theoretical limit state model of the system. This calculation is based on the assumption that at the ultimate limit state all pins reach, as the dissipative elements of the system, their moment capacity.

2.4.2. Design for linear elastic analysis

The design rules are intended to ensure that yielding, will take place in the pins prior to any yielding or failure elsewhere. Therefore, the design of buildings with FUSEIS pin link is based on the assumption that the pins are able to dissipate energy by the formation of plastic bending mechanisms. The following design methodology may be applied:

1) Instructions for the simulation of the frame and pin links in an elastic model.
2) Static and Modal Response Spectrum Analysis are performed and all members not affected by the FUSEIS system are dimensioned. Recommended q factor equal to 3.
3) Limitation of interstorey drift.
4) Influence of 2nd order effects.
5) Dissipative elements verifications. The pins shall be verified to resist the internal forces and moments of the most unfavorable seismic combination and fulfill the conditions for the axial forces, shear force and bending moment capacity, as well as the limitation of the length and the rotation of the pins.
6) Global dissipative behavior.
7) Capacity design of non-dissipative elements. The FUSEIS columns, receptacle beams and their connections are designed under the capacity design forces ($N_{CD,Ed}$, $V_{CD,Ed}$, $M_{CD,Ed}$), based on the minimum pin over-strength factor of the building. The full section of the pin is designed with adequate plastic moment capacity to ensure full plastification of the RBS section of the pin.

2.4.3. Design for non-linear static analysis (pushover)

The structural model used for elastic analysis can be extended to include the response of structural elements beyond the elastic state and estimate expected plastic mechanisms and the distribution of damage. Instructions for the simulation of the frame and hinge properties of the pins are given. Figure 6 summarizes the proposed non-linear properties.

Point	$M/M_{pl,pin}$	$\theta/\theta_{pl,pin}$
A	0	0
B	1	0
C	2	100
D	0,5	100
E	0,5	150
Acceptance criteria ($\theta/\theta_{pl,pin}$)		
IO	30	
LS	45	
CP	60	

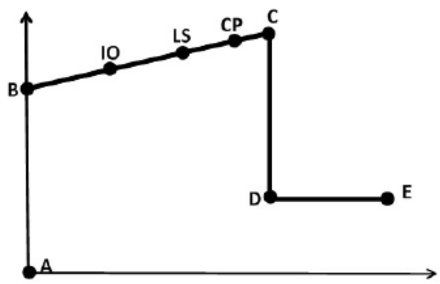
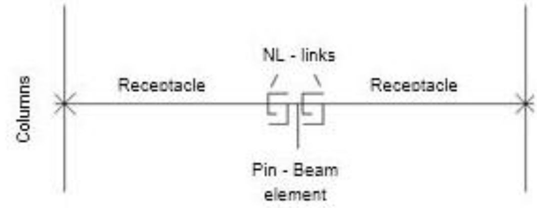


Figure 6: Proposed non-linear hinge parameters for the pins

2.4.4. Design for non-linear dynamic analysis

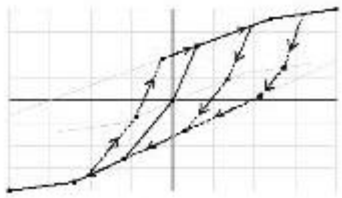
It shall be performed in order to define time-dependent response of steel buildings when designed according to the provisions of EN1998-1-1 under real earthquake conditions. The analysis provides the capability to restrict damage after a seismic event by evaluating and eliminating the residual drifts of the structure. If the FUSEIS pin link system is appropriately designed, it can work as a self-centring system, with practically zero residual drifts. Instructions for the simulation of the frame and hinge properties of the pins are given. Figure 7 summarizes the proposed non-linear properties.



a) Simulation of pins

Point	Rotation	Moment
1	$-10\theta_{pl,\,pin}$	$-2M_{pl,\,pin}$
2	$-2\theta_{pl,\,pin}$	$-1M_{pl,\,pin}$
3	0	0
4	$2\theta_{pl,\,pin}$	$1M_{pl,\,pin}$
5	$10\theta_{pl,\,pin}$	$2M_{pl,\,pin}$

b) Multi-linear force – deformation definition



c) Multi-linear plastic kinematic model

Figure 7: Proposed non - linear links simulation for non-linear dynamic analysis

2.5 Analyses on 2D building frames

Equations, element properties, design recommendations, critical checks and proposed behavior factor, included in the Design Guide, were verified through numerical analyses on real 2D building frames with FUSEIS pin links with the use of the software SAP2000. Initially the frames were designed through elastic analysis at ULS and SLS. Non-linear static and dynamic analyses followed to investigate their behavior beyond the elastic range and confirm the behavior factor q=3.

The case study presented in the information brochure was based on the extraction of a plane frame from a five-story composite building. The frame consisted of a semi-rigid PF frame (partially fixed moment frame) with three 6m bays and one FUSEIS pin link system applied at its end to provide lateral resistance. The columns had rectangular hollow sections (RHS) and the floor beams composed of steel beams with wide flange I-sections (HEA-Type) acting compositely with the concrete slabs (C25/30, B500C), except at beam ends where the concrete slab was not connected to the steel beam. The FUSEIS system consisted of a pair of hollow strong columns at a center-to-center distance of 2.0 m and five links per story with circular pins of a net length of 200 mm. A link was provided at the foundation level and the receptacle beams had rectangular and square hollow sections (RHS, SHS) and were connected rigidly to the system columns.

The analysis of the building is detailed described following the design guides. Implementation of Design Rules, non-linear static analysis, evaluation of the behavior factor q, non-linear dynamic analysis, residual roof and interstorey drifts, low-cycle fatigue checks and finally Incremental Dynamic Analysis (IDA) are the steps of the design.

2.6 Field of application

The innovative fuses may be applied to multi-story steel buildings and substitute the conventional systems used worldwide (such as concentric and eccentric braced frames, moment resisting frames etc.) by combining ductility and architectural transparency with stiffness.

3 CASE STUDIES

3.1 Introduction

The case study presented hereafter, was studied for Work Package 4 of the INNOSEIS project. The design of the building was performed according to the provisions of the Eurocodes and the design guidelines. Initially the building was designed through elastic analysis a ULS and SLS. Nonlinear static analysis followed to investigate its behavior beyond the elastic range and confirm the behavior factor q=3.

3.2 Geometry and assumptions

The building was a 4-storey composite building, consisted of four semi-rigid PF frames (partially fixed moment frame) with three 8m bays in each direction (Fig. 8, 9). Two FUSEIS pin link systems were applied on each of the external frames to provide seismic resistance. The columns had I-section (HEB type), the main and the secondary floor beams composed of steel beams with IPE and HEA sections correspondingly, both acted compositely with the concrete slabs (C25/30, B500C).

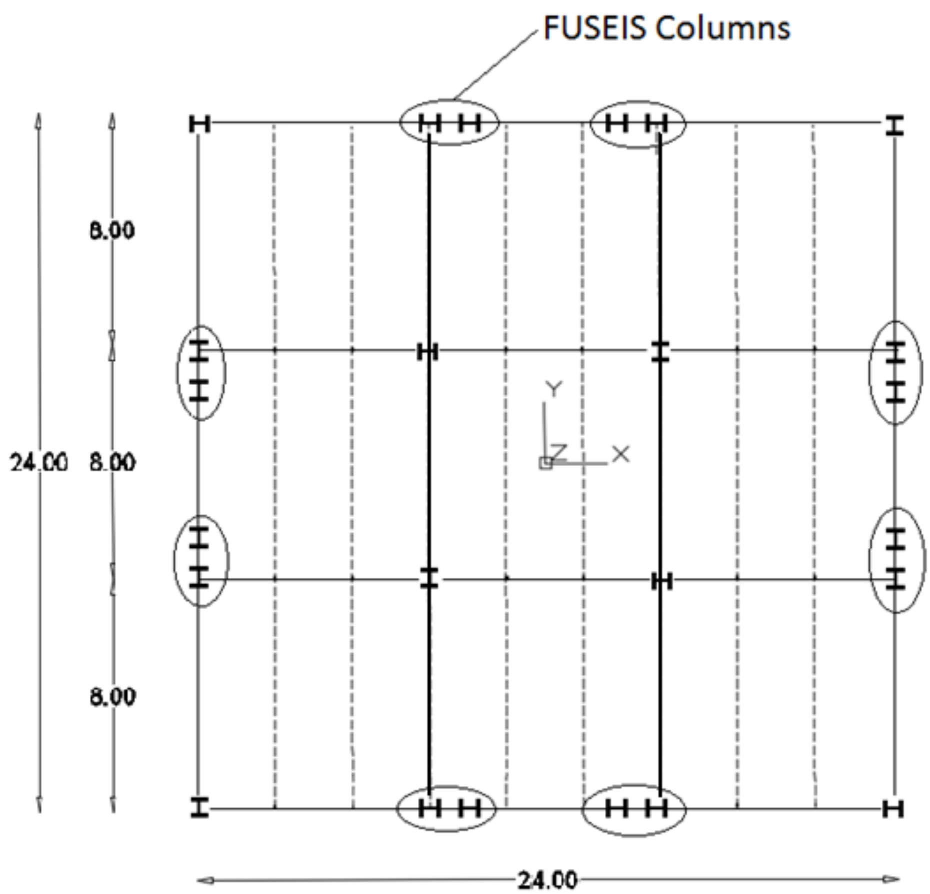


Figure 8: Plan view of the building, FUSEIS system potition

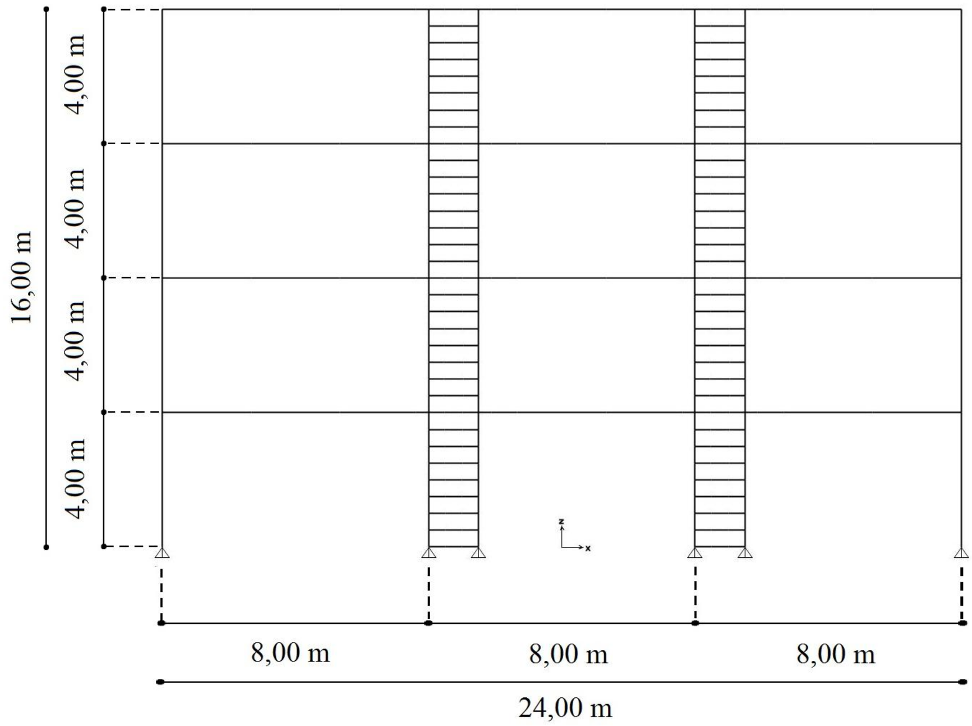


Figure 9: Side view of the building

The system consisted of a pair of strong columns (HEB 700) at a center-to-center distance of 1.5m and nine pin-links per story, rigidly connected to the system columns. The resulting cross sections for main beams was IPE500, for secondary beams HEA 200 and for columns varied from HEB200 to HEB280. Table 1 summarizes the diameters of the pins and the cross section of the system columns in each system, starting from the foundation level. The dissipative pins had lower steel grade (S235) than the rest of the structural member (S355).

	Reduced Diameter Pins Φ(mm)	Full Diameter Pins Φ(mm)	System columns
×2	120	160	HEB 700
×3	110	150	HEB 700
×4	105	130	HEB 700
×4	100	130	HEB 700
×4	95	130	HEB 700
×4	90	130	HEB 700
×4	85	130	HEB 700
×4	75	130	HEB 700
×4	70	120	HEB 700

Table 1: Cross sections of pins and columns

Gravity and seismic loads are summarised in Table 2.

Vertical loads	
dead loads (composite slab + steel sheeting)	2.75 kN/m²
superimposed loads for intermediate floors:	0.70 kN/m²
superimposed loads for top floor:	1.00 kN/m²

perimeter walls:	4.00 kN/m
total live load:	3.80 kN/m²:
Elastic response spectra	Type 1
Peak ground acceleration	0.30g
Importance class II	$\gamma_I = 1.0$
Ground type	C
Proposed behavior factor	3
Seismic combination coefficient for the quasi-permanent value of variable actions	ψ_2=0.30

Table 2: Loads assumptions

3.3 Simulation

The modelling, analysis and design of the buildings, was performed with the finite element program SAP2000. The structural model was a linear-elastic model with beam elements. The beam elements representing the FUSEIS pin links were divided in three parts with different cross sections: the full diameter pin at the ends and the weakened pin in the middle (Fig. 10). The joints between the pins and the system columns were considered as rigid. The joints between the floor beams and the system columns were considered as simple. Column bases were designed and formed as pinned to prevent a moment transfer to the foundation (Fig. 11).

Figure 10: Division of FUSEIS pins

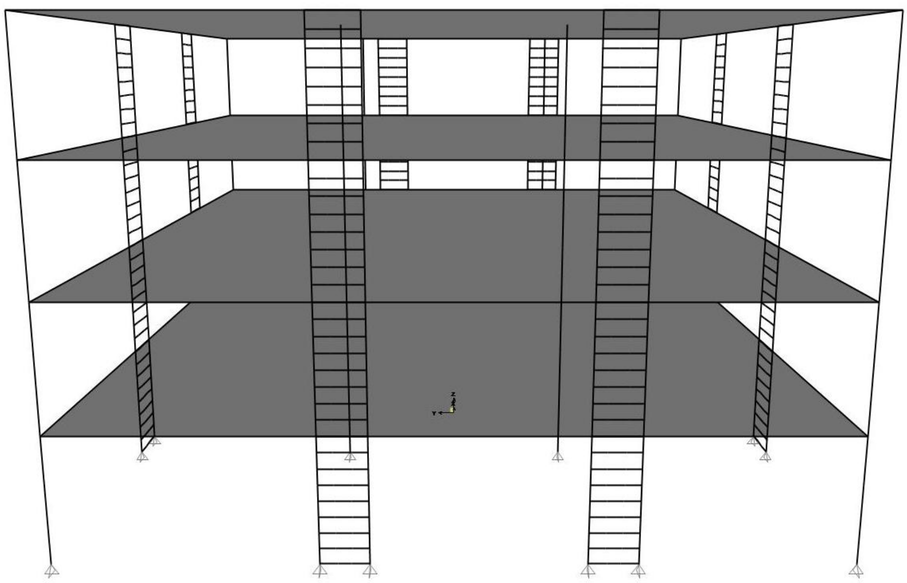


Figure 11: 3D view of the model in SAP2000

3.4 Seismic design

It is noted that for the seismic design the following conditions were to be fulfilled, in accordance to the design guidelines and EN1998 rules.

3.4.1. Limitation of interstory drift

Considering that the building has ductile non-structural elements the following equation is checked:

$$d_r \cdot v \leq 0.0075 \cdot h = 0.0075 \cdot 4 = 30mm \tag{1}$$

Where ν =0.5 is a reduction factor on the design displacements due to the importance class of the building (ordinary buildings) and h is the story height. Table 3 includes the results of the analysis. The selection of the columns' and the receptacle beams' sections was defined by this check.

Story	u_x (mm)	d_{ex} (mm)	$q*d_{ex}$ (mm)	$v*d_{rx}$	Check	0.0075h
1ος	11.8	11.8	35.4	17.7	≤	30
2ος	28.0	16.2	48.6	24.3	≤	30
3ος	46.8	18.8	56.3	28.1	≤	30
4ος	65.7	19.0	56.9	28.4	≤	30

Table 3: Limitation of interstory drift in x direction

3.4.2. 2nd order effects

A linear buckling analysis for the seismic combination 1.0G+0.3φQ was carried out in order to control 2nd order effects. From this analysis, the critical buckling modes and the corresponding buckling factors were derived. The buckling mode of the frame in x direction is given in Figure 12.

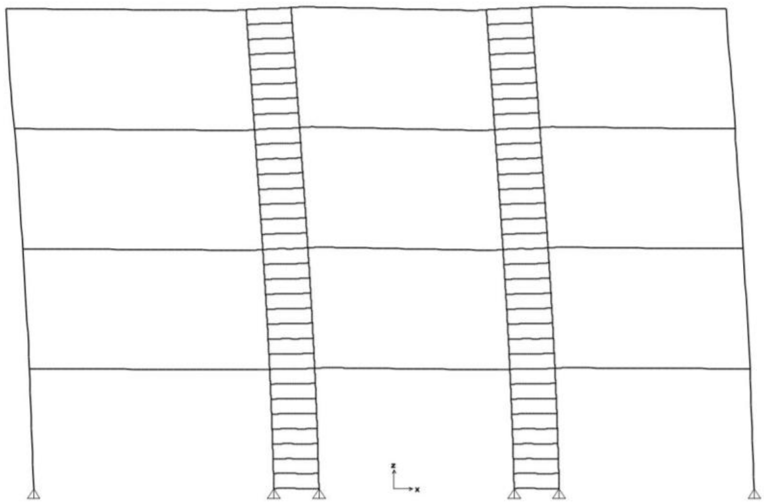


Figure 12: 1st buckling mode

The values of coefficient θ were calculated from the critical buckling factors, in order to check whether 2nd order effects should be taken into account. Since θ<0.1 for all cases (Table 4), 2nd order effects were safely neglected.

Direction	Critical buckling factors	$\theta = q / \alpha_{cr}$	limit	Seismic load multiplier
x	37.00	0.081	0.1	1.00
y	37.14	0.081	0.1	1.00

Table 4: 2nd order effects

3.4.3. Dissipative elements - pins

The FUSEIS pins were designed to resist the forces of the most unfavorable seismic combination 1.0·G+0.3·φ·Q+Ex. The minimum required length to ensure the development of a bending mechanism at the pins is calculated from Equation (2) and ranges between 154mm and 261mm. Therefore, the lengths of the weakened part of the pins were taken larger than the minimum, varying along the vertical axis.

$$l_{pin,w} \geq 6 \cdot M_{pl,pin} / V_{pl,pin} \quad (2)$$

Tables 5 to 7 summarize the results of all the pin verifications, in x direction. The pin overstrength values Ω were also used to check the global dissipative behavior of the system which is ensured when the Ω values of all the pins in all stories differ no more than 25% of its minimum value. It was calculated that maxΩ/minΩ= 1.24.

Reduced Diameter Pins Φ(mm)	N_{Ed} (kN)	$N_{pl,pin,Rd}$ (kN)	$\frac{N_{Ed}}{N_{pl,pin,Rd}} \leq 0.15$
120	1.04	2657.79	0.00
110	1.26	2233.28	0.001
105	4.50	2034.87	0.002
100	4.30	1845.69	0.002
95	4.32	1665.73	0.003
90	4.18	1495.01	0.003
85	4.15	1333.51	0.003
75	7.60	1038.20	0.007
70	7.60	904.39	0.008

Table 5: Check of axial forces

Reduced Diameter Pins Φ(mm)	$V_{CD,Ed}$ (kN)	$V_{pl,pin,Rd}$ (kN)	$\frac{V_{Ed}}{V_{pl,pin,Rd}} \leq 0.50$
120	267.90	1534.474	0.175
110	206.80	1289.385	0.160
105	160.30	1174.832	0.136
100	129.25	1065.607	0.121
95	119.18	961.710	0.124
90	94.00	863.142	0.109
85	84.77	769.901	0.110
75	54.83	599.404	0.091
70	47.84	522.147	0.092

Table 6: Check of shear forces

Reduced Diameter Pins	M_{Ed} (kN.m)	$M_{pl,pin,Rd}$ (kN.m)	$\frac{M_{Ed}}{M_{pl,pin,Rd}} \leq 1.00$

Φ(mm)			
120	58.79	66.975	0.872
110	46.112	51.700	0.892
105	34.391	44.885	0.766
100	29.187	38.775	0.753
95	26.341	33.370	0.789
90	22.004	28.200	0.780
85	19.754	23.735	0.832
75	12.169	16.450	0.740
70	10.204	13.395	0.762

Table 7: Check of bending moments

It was also checked that the pin chord rotations were below the limit suggested by design guides (Table 8). It was verified that:

$$\theta_{pin} \leq \theta_{pl,pin} = 13.8\% \quad (3)$$

Reduced Diameter Pins Φ(mm)	θ_{pin} (%)	check	$\theta_{pl,pin}$
120	2,66%	≤	13,80%
110	2,66%	≤	13,80%
105	2,37%	≤	13,80%
100	3,04%	≤	13,80%
95	3,25%	≤	13,80%
90	3,52%	≤	13,80%
85	3,77%	≤	13,80%
75	3,55%	≤	13,80%
70	3,81%	≤	13,80%

Table 8: Pin rotations θ_{pin} (%)

3.4.4. Non-dissipative elements verifications

The non-dissipative elements, the system columns, full section pins and their connections, were capacity designed for increased values of internal forces compared to the ones derived from the analyses with the most unfavorable seismic combination, to ensure that the failure of the pins occurs first.

The system columns were designed following capacity design criteria in accordance with Equations (4) - (6), taking into account the minimum overstrength factor Ω of all the pins, the material overstrength factor, an additional overstrength factor α=1.5 derived from the nonlinear analysis and the seismic load multiplier β derived from the limitation of the 2nd order effects. The utilization factors of the system columns and the receptacle beams were calculated according to the provisions of EN1993-1-1 and the higher was equal to 0.83.

$$N_{CD,Ed} = N_{Ed,G} + 1.1 \cdot a \cdot \gamma_{ov} \cdot \Omega \cdot N_{Ed.E} \quad (4)$$

$$M_{CD,Ed} = M_{Ed,G} + 1.1 \cdot a \cdot \gamma_{ov} \cdot \Omega \cdot M_{Ed.E} \quad (5)$$

$$V_{CD,Ed} = V_{Ed,G} + 1.1 \cdot a \cdot \gamma_{ov} \cdot \Omega \cdot V_{Ed.E} \quad (6)$$

The moment resistance of the full pin section shall be verified at its contact area with the face plate of the receptacles (Table 9), in accordance with:

$$\frac{M_{CD,Ed}}{M_{pl,Rd}} \le 1.0 \tag{7}$$

Where $M_{CD,Ed} = l/l_{pin} \cdot M_{pl,pin,rd}$ is the capacity design bending moment (l is the length between the face plates of the receptacles) and $M_{pl,Rd}$ is the design bending moment of full pin section.

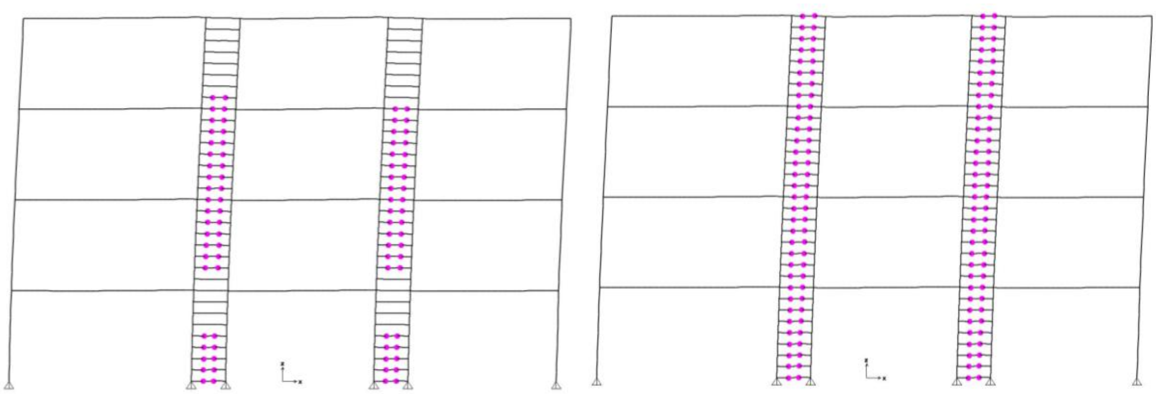
Reduced Diameter Pins Φ(mm)	$M_{CD.Ed}$ (kNm)	$M_{pl,Rd}$ (kNm)	$\frac{M_{CD,Ed}}{M_{pl,Rd}} \le 1.00$
120	99.12	158.86	0.62
110	76.52	130.90	0.58
105	59.31	85.31	0.70
100	47.82	85.31	0.56
95	44.10	85.31	0.52
90	34.78	85.31	0.41
85	31.36	85.31	0.37
75	20.29	85.31	0.24
70	17.70	66.98	0.26

Table 9: Check of the resistance of the full pin section

3.5 Non-linear static analysis (Pushover)

Nonlinear static (pushover) analysis was performed to verify the collapse mechanism and check the behavior factor used in the linear analysis. Analysis was done in both x and y directions, in both Modal and Uniform shapes. The results presented hereafter are in accordance with the fundamental mode of vibration including P–Delta effects. Nonlinear plastic hinges of bending type M3 were assigned at the ends of the weakened parts of the pins and the full diameter part of them. The hinge properties of the rotational springs that simulated the semi-rigid joints were also of bending type (M3 hinge) and were calculated for positive and negative moments, while in columns the interaction between bending moments and axial forces (P-M3 hinges) were accounted for.

The plastic hinge distribution at first yield, at the performance point and at the maximum experimental intestory drift are given in Figure 13. It is observed that the columns remained elastic and that plastic hinges formed only at the pins and the ends of the beams with the semi - rigid frame.



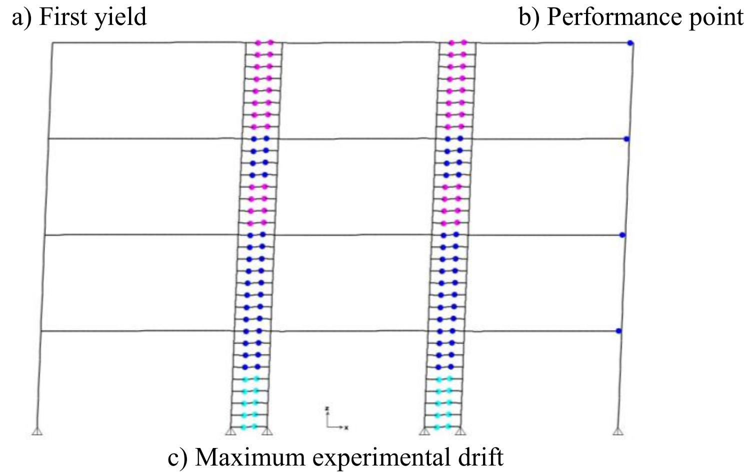


Figure 13: Deformed frame and plastic hinge formation

The calculated ductility, overstrength and behavior factors, of the FUSEIS+PF frame are given in Table 10. The calculated q-factor is significantly higher than 3, which was a conservative value.

q_μ	Ω	q
6.78	1.22	8.26

Table 10: Calculated behavior factors q

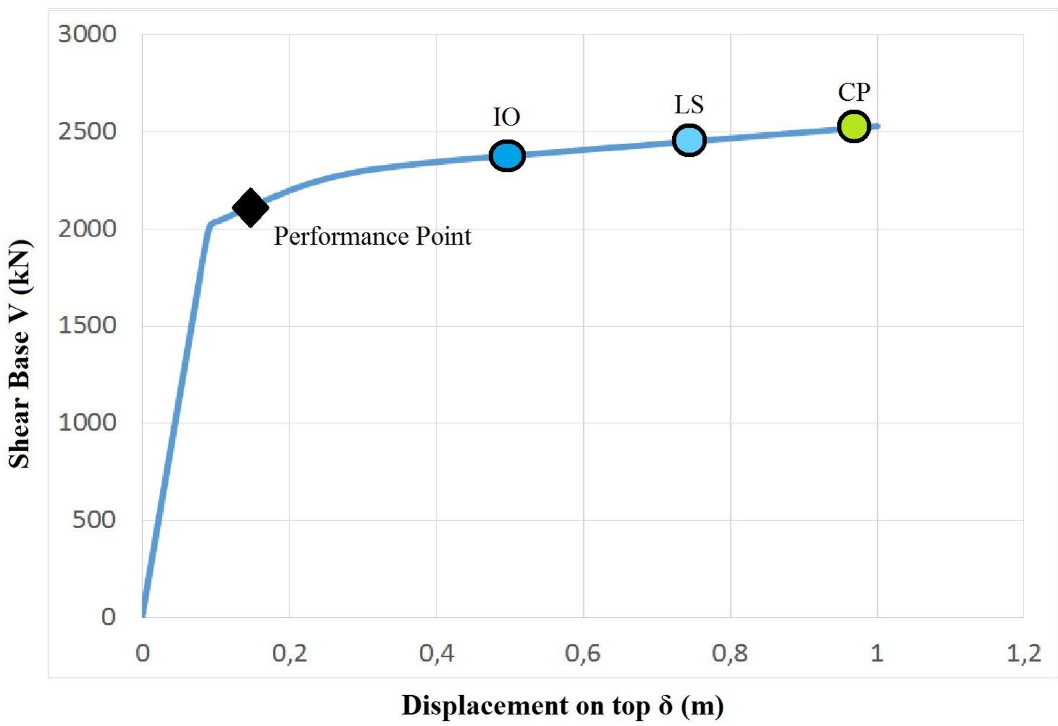


Figure 14: Pushover curve (Modal Distribution, x direction)

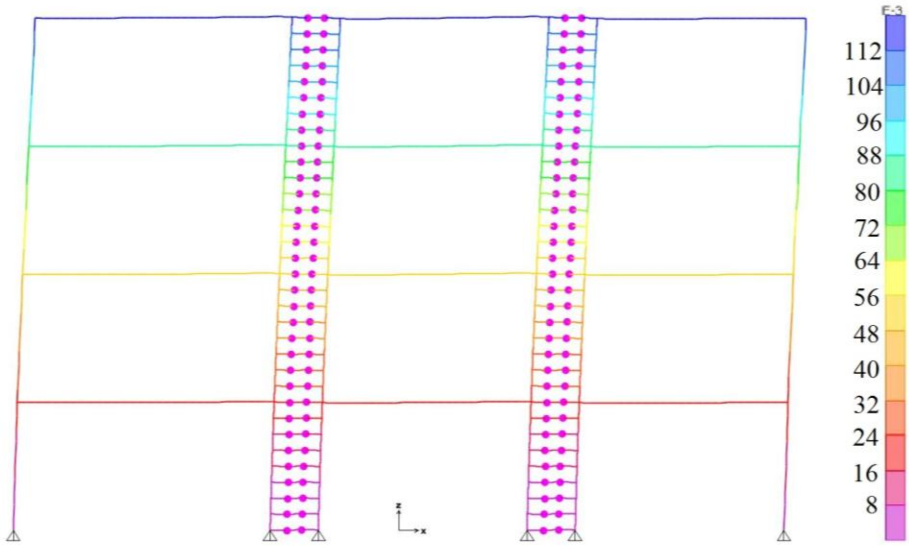


Figure 15: Deformed shape and displacement at Performance Point (Non-linear static analysis)

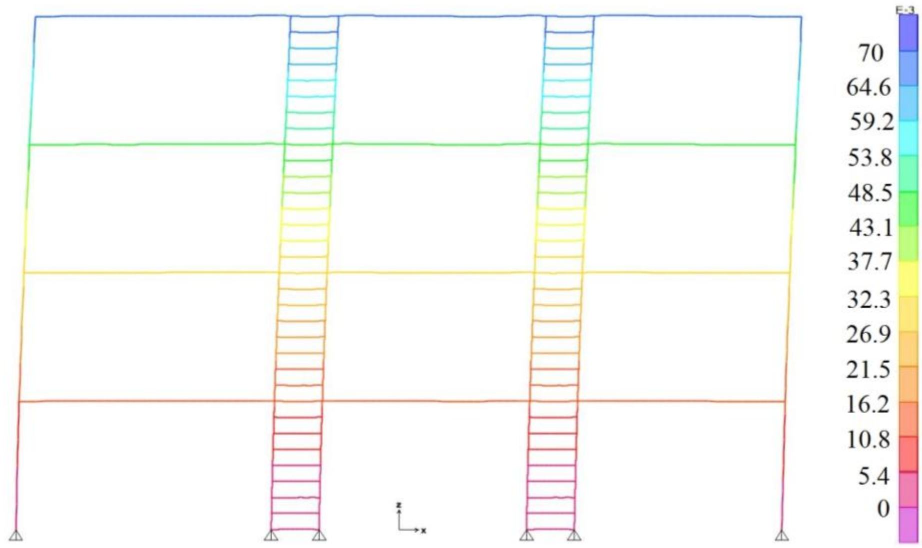


Figure 16: Deformed shape and displacement from Response Spectrum Analysis (elastic analysis)

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