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# SEISMIC DESIGN OF STEEL FRAMES WITH FUSEIS BEAM LINK ENERGY DISSIPATION SYSTEMS

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**Keywords:** Seismic design, energy dissipation, FUSEIS beam link system, INNOSEIS project, FUSEIS project, MATCH project.

**Abstract.** *Within the EU funded project INNOSEIS different seismic devices developed in earlier projects are worked up with the aim to provide information sheets and design guidelines for an easy practical implementation of these systems. One of these seismic protection systems is the FUSEIS beam link concept. The main idea is to use two closely spaced strong columns rigidly connected by several beams, resulting in a Vierendeel girder in upright position. Energy dissipation is originated by plastification of the connecting girders, similar as in seismically designed moment resisting frames. Forming the lateral load resisting system but not taking part intentionally in the vertical load transfer, the girders can be inspected and replaced much more easily after a strong earthquake.*

*In this paper, first the FUSEIS beam link system is described in detail supported by results of experimental tests. Behaviour and main mechanical principles are outlined. Further on, three case studies consisting of steel office buildings of different heights are designed for seismic loads using the FUSEIS beam link solution.*


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## 1 INTRODUCTION

During an earthquake, a building may have to resist strong demands regarding strength, stiffness and energy dissipation. Several strategies exist on how the building is able to cope with these high demands. Some classical approaches as the ‘weak beam – strong column’ concept used in moment resisting frames work well in preventing a total collapse of the structure. However, after the design basis earthquake the main structure may be severely damaged and a rebuilding of the structure may be more economically and practically than repairing the structure. The main reason is, that the intended energy dissipation zones are also a part of the gravity load carrying system, and thus replacement of plasticized regions of the structure is difficult.

The main advantage of the innovative FUSEIS beam link system is to transfer the moment resisting frame responsible for the lateral resistance into a smaller, separated region of the structure. While decoupled from the gravity load bearing mechanism, replacement of the concentrated fuse elements is much more easy and practical. Energy dissipation is foreseen solely at these fuses, while the rest of the structure is protected by capacity design.

In this paper first the FUSEIS beam link system, which has been developed and experimentally tested in recent European research projects (FUSEIS [1], MATCH [2]), is described in detail. Main experimental test results are mentioned further on. Corresponding numerical simulations are well capable of representing the experimental findings. Finally, it is shown by means of different case studies, how to design a steel frame structure for seismic loads with the FUSEIS beam link system.

## 2 DESCRIPTION OF FUSEIS BEAM LINK SYSTEM

The FUSEIS beam link system is composed of two closely spaced strong columns rigidly interconnected by multiple beams. The beams run from column to column and can be of different cross section types, as for example RHS, SHS, CHS or I-shaped sections. The general layout is shown schematically in Figure 1. The FUSEIS beam link system resists lateral loads as a vertical Vierendeel beam, mainly by combined bending and shear of the beams and axial forces of the columns. The dissipative elements of the system are the beam sections between the columns. These elements are not generally subjected to vertical loads, as they are placed between floor levels.

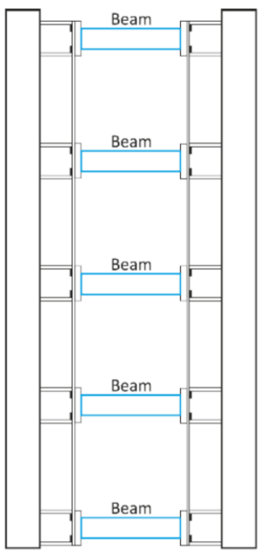



**Figure 1: FUSEIS beam link system: general layout**

The seismic resistance of a building may be obtained by appropriate provision of a number of such systems in the relevant directions. See Figure 2 for an exemplary assembly of several FUSEIS beam link systems in a 3D steel frame structure. When beam-to-column connections of the building are formed as simple, this system alone provides the seismic resistance of the building. When the connections are rigid or semi-rigid, it works in combination with the overall moment resisting frame. In both cases the beam-to-system columns connections should be formed as simple, since the system is not intended to consist a gravity load carrying part of the structure.

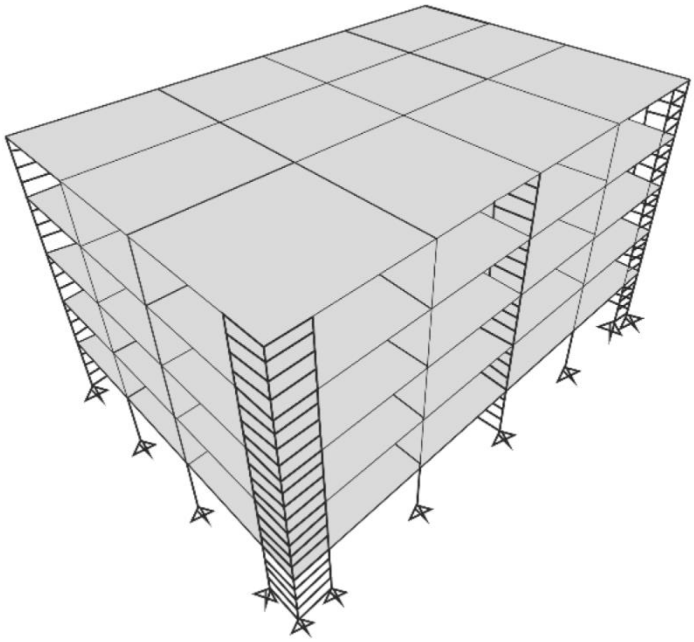


**Figure 2: Exemplary assembly in steel frame structure [1]**

Aiming to minimize damage at the foundation locations pinned connections at the column bases are proposed. At multi-storey buildings the column bases may be pinned or fixed, analytical investigations showed that the difference in the response was not significant. The fuses-to-column joints are formed as rigid to enable the Vierendeel action and are designed to have sufficient overstrength in order to achieve energy absorption only in the fuses. Bolted end-plate connections which enable an easy replacement of the beams should be used.

Beams may have closed sections (RHS) or open sections (I- or H- sections). Considering a typical floor height of 3.4 m, four or five beams may be placed per storey. Their beam height depends on the required stiffness with the provision to leave the necessary vertical spacing between them. RHS sections are more beneficial to open sections due to their larger flexural and torsional rigidities and strength. Beam sections may vary between floors, following the increase of storey shear from the top to the base of the building. Beams may also vary within the floor, either in respect to their cross-sections or to the vertical distance between each beam, as illustrated in Figure 3. Columns may be of open or closed section. Open sections are more beneficial, since they offer an easier connection to the beams. When closed sections are used, a T-section can be welded to the column in order to offer the advantage of easier connection.

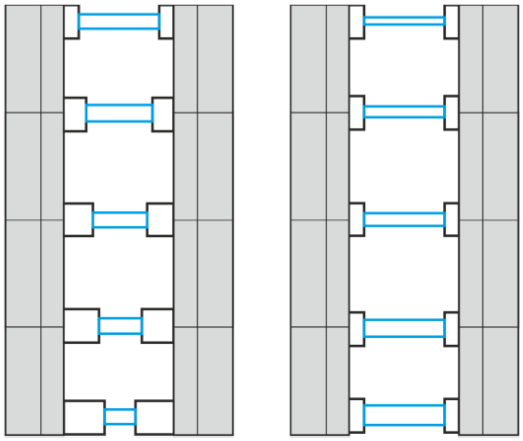


**Figure 3: Adjustment of FUSEIS beam link system to storey shear by variable beam lengths (left) or variable cross sections (right)**

The most severe disadvantage of conventional frame typologies, such as MRF, CBF or EBF, is their inability to be easily repaired after a strong seismic event. Concerning moment-resisting frames, the beams and their connections have to be exchanged. As both of these elements belong to the gravity loading resistant system, their replacement is difficult. In eccentrically braced frames, the links, that are short parts of the beams, must be replaced. The damage in concentrically braced frames is expected in the braces, which are also difficult to exchange as they are long and heavy. These conventional structural systems can be substituted by the innovative FUSEIS beam link. Hereby the new system has the following advantages:

- Inelastic deformation only occurs in the dissipative beam link elements
- If plastically deformed, the beam link can be easily replaced as they are not part of gravity load carrying system and are moreover easy to handle
- To keep the architectural layout unaffected by the seismic resistant system, the FUSEIS beam link system may be positioned in small areas of the building
- At the same time, the beam link may be used as visible parts of the building to indicate its seismic resistant system
- For appropriately selected sections of the fuses, or by varying the length of each beam link, sequential plastification may be achieved

In order to ensure that dissipation of energy only takes place in the beam links, the fuses-to-column joints are formed rigidly and own a sufficient over-strength. Moreover, the beam links are attached through bolted endplates, enabling an easy replacement if the beam links should be deformed after a seismic event.

**Figure 4: Different section types for FUSEIS beam links with reduced beam sections (RBS): RHS or SHS, CHS and IPE- or HEA-section**

Intending to protect the beam-to-column connection against yielding and fracture, the FUSEIS beam links should be designed in such a manner that the plastic hinge forms away from the connection area. Therefore, reduced beam sections (RBS) are foreseen at the end of the beams, see Figure 4. Constant, tapered or radius cut shapes are possible to reduce the cross sectional area. In order to minimize stress concentrations, the radius cut is superior compared to other types of cuts. The typical length of plastic hinges in steel beams has the order of half the beam depth. Therefore, the reduced beam section, where the plastic hinge shall form, should be located at least that distance away from the connection. As an alternative to reducing the beam section, the connection region could be strengthened by means of additional stiffening plates.

## 3 EXPERIMENTAL INVESTIGATIONS ON FUSEIS BEAM LINKS

Test on the FUSEIS beam link system have been conducted during two European projects, namely the FUSEIS [1] and MATCH [2] project. Beam links have been investigated individually. In total 40 tests have been conducted for individual beam links, 23 tests during the FUSEIS project and 17 during the MATCH project. The test program covered variations of section types, material, length of beam links and loading conditions. Individual beam links have been placed between two girders of a four point hinged frame (Figure 5). The connection between test frame and FUSEIS beam link was obtained by bolted connections. A load actuator with a capacity of ± 200 mm was attached to the upper girder of the test frame, such that it could be moved horizontally. Picture of the test frame setup and inserted beam link are shown in Figure 6.

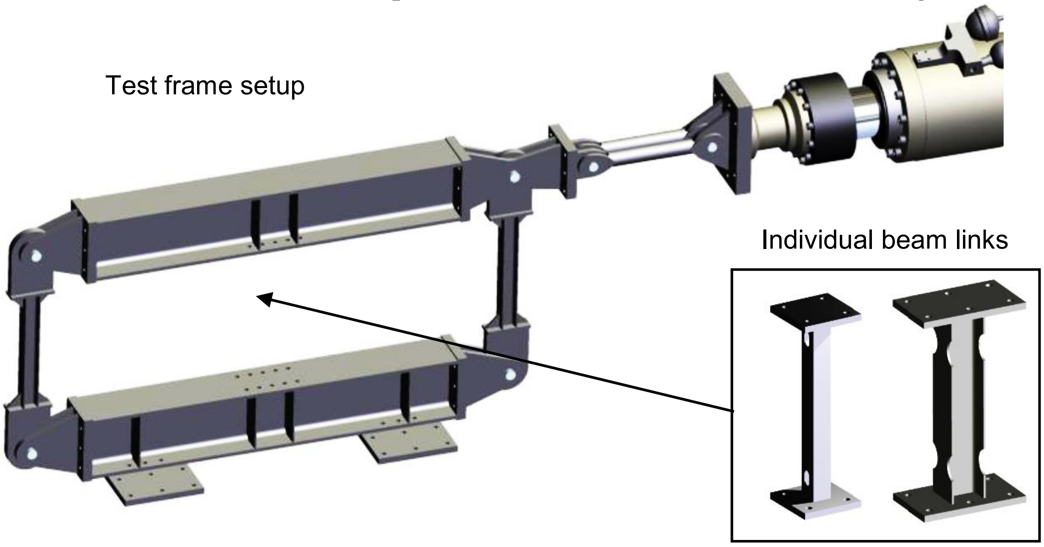



**Figure 5: Illustration of test frame setup for testing of individual beam links**

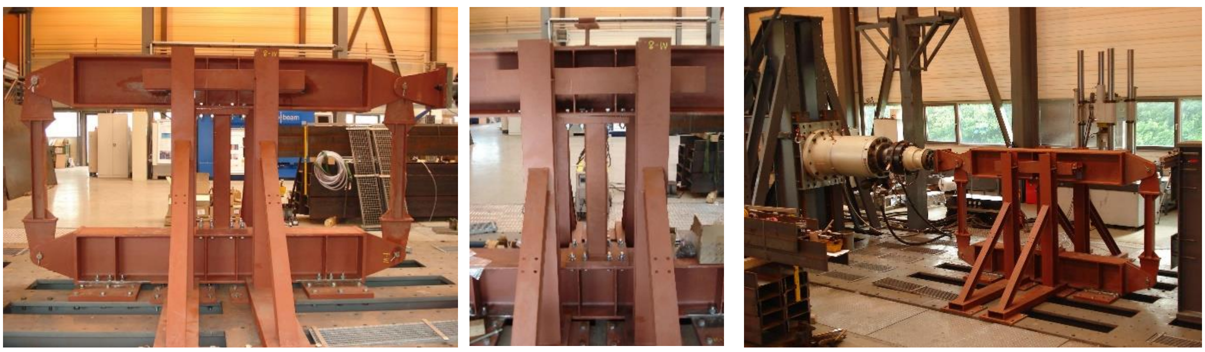


**Figure 6: Picture of test frame equipped with individual FUSEIS beam link with SHS type**

### 3.1 Results of monotonic tests

Long test specimens with a beam link length of 900 mm showed very ductile behaviour with maximum displacements of more than 150 mm before collapsing. In comparison to these specimens the maximum displacement of the shorter specimens with a length of 500 mm reached about 80 mm, whereas the hardening effect after exceeding the elastic range was much more significant in case of I-sections than CHS. This was most likely due to the high utilization degree of shear loading. An exemplary force displacement curve is shown in Figure 7, while the corresponding damage pattern can be seen in Figure 8.

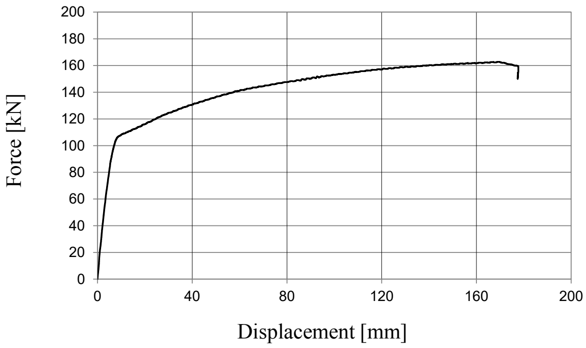



**Figure 7: Force displacement curve for IPE section**

**Figure 8: Damage pattern in IPE section after monotonic loading**

### 3.2 Results of cyclic tests

As reference for the testing procedure the "ECCS – recommendation for assessing the behaviour of structural steel elements under cyclic loads" [10] was used. The maximum displacement value of 60 mm (4% interstorey drift) was only reached with some of the fuses. Other fuses were not capable of this maximum displacement level. However, most of the fuses showed a very ductile behaviour during cyclic loading. Although cracks and buckling effects occurred quite early during some of the tests – at displacements of approximately 20 to 30 mm – a high ductility was achieved. In most cases a distinctive ductile behaviour with cracks in the base material and a slow crack propagation could be observed. The locations and the shapes of buckles were strongly dependent on the cross-section, the length of the specimen and the magnitude of loading. The points at which the first cracks occur are in general depending on these buckles. Only a few specimens failed in the area of the heat affected zone and a less ductile failure was noticed. The main remarks from the execution of the tests can be summarized as follows:

- The load-displacement curves between specimens of the same type had significant differences.
- Cracks appeared very early in some of the specimens. In spite of these cracks the specimens had considerable remaining capacity.
- The initial fillet welding of the SHS profiles was not sufficient. It is recommended to use full seam butt welds instead of fillet welds.

Exemplary hysteretic curves and corresponding damage patterns are shown in Figure 9.

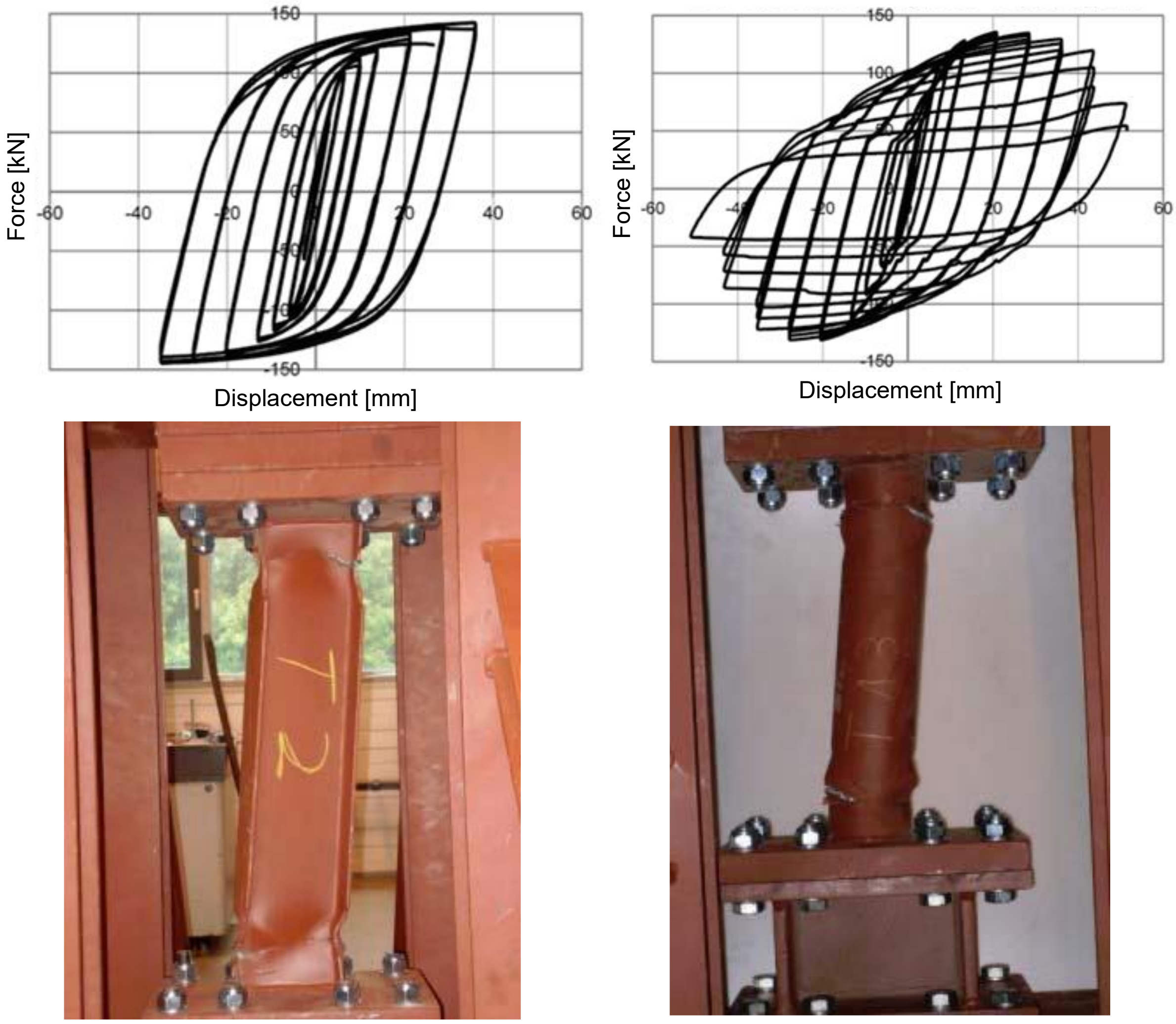
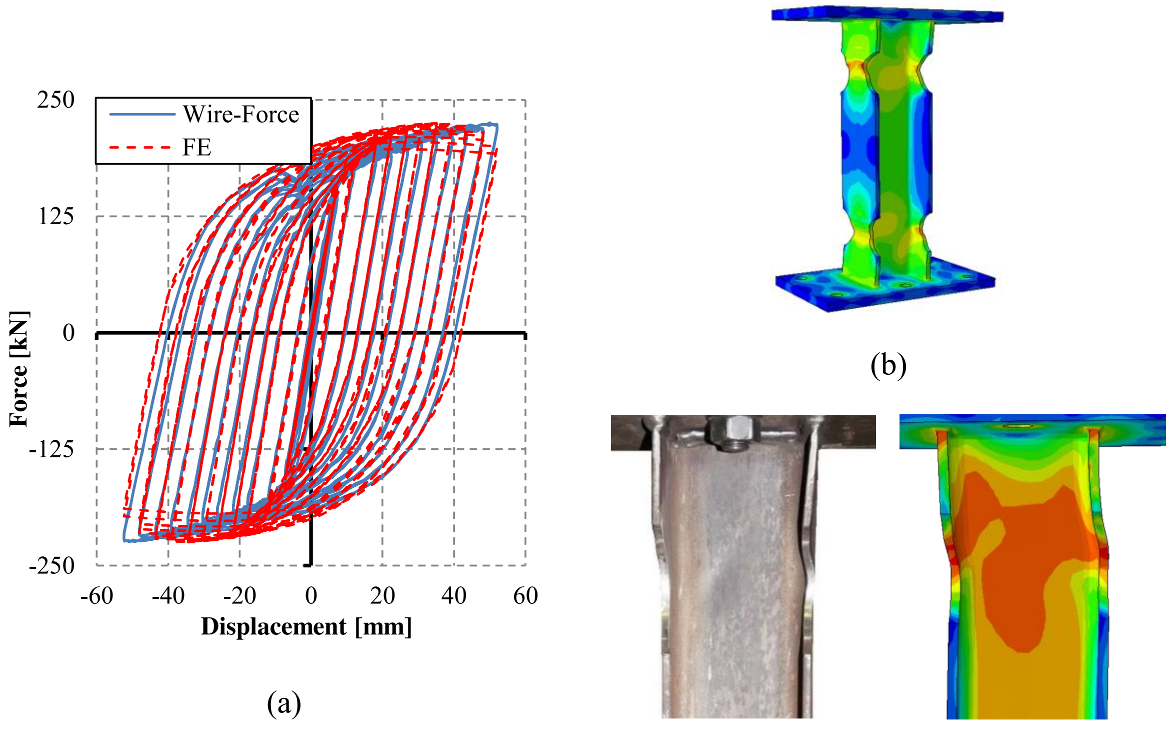



**Figure 9: Exemplary hysteretic behaviour and damage pattern for I-section (left) and CHS profile (right) after cyclic loading**

### 3.3 Numerical simulation

The experimental tests have been simulated by means of finite element methods. An innovative damage model has been incorporated in order to assess on the failure of the specimen [8]. A solid model has been set up in ABAQUS using C3D8 elements. A modified version of the Armstrong-Frederick kinematic hardening model has been applied, while material parameters were determined by small scale material tests. A fine mesh with an average element size of 7 to 9 mm has been used, in order to realistically capture the relevant failure mode. Figure 10 shows exemplarily the measured and simulated force displacement curve, the solid model of an individual FUSEIS beam link along with its stress distribution and the displaced shape, both observed and simulated. In general the simulations fit the experimental results very well, also damage locations and behaviour could be predicted almost exactly.




(c)

**Figure 10: Comparison between experimentally and numerically obtained force displacement curve (a), finite element model of FUSEIS beam link with stress distribution (b), comparison between observed and simulated displacement patterns (c). [9]**

# 4 SEISMIC DESIGN WITH FUSEIS BEAM LINK SYSTEM

## 4.1 Description of case studies

During the INNOSEIS project in total three office buildings with different number of storeys had to be designed according to Eurocode 3 [3] and 8 [4][5]. The seismic resistance had to be provided solely by means of the FUSEIS beam link system. Figure 11 shows the side view for the three buildings: (a) the low-rise frame with two storeys, (b) the medium-rise frame with four storeys and (c) the high-rise frame with eight storeys. The main geometric parameters are identical for all three case studies: 3-bay frames with a storey height of 4 meters and a distance between the centerlines of columns of 8 meters in both directions. The common plan view is shown in Figure 12. The slabs are composite ones and secondary beams transfer loads into the main frame. S355 steel is used for columns and girders. Firstly, the buildings have been designed for vertical loads only, taking into account different construction stages [6]. The final outcome for beam and column cross sections is listed in Table 1. Secondly, seismic loads have been taken into consideration redesigning the structure by placing a FUSEIS beam link system at each frame, as indicated in Figure 12.

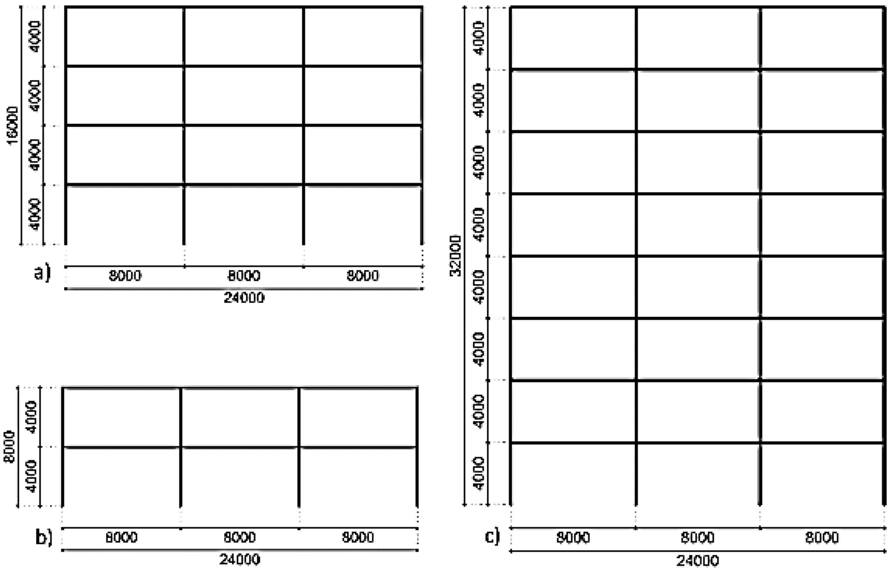



**Figure 11: Layout of case studies (a) low-rise, (b) mid-rise and (c) high-rise building [6]**

**Table 1: Cross sections of columns and girders obtained for vertical load design (according to [6])**

| | Low-rise | | Medium-rise | | High-rise | |
|---|---|---|---|---|---|---|
| Primary girder | IPE 500 | | IPE 500 | | IPE 500 | |
| Secondary girder | HEA 200 | | HEA 200 | | HEA 200 | |
| Columns per floor | Centre | Perimeter | Centre | Perimeter | Centre | Perimeter |
| 1 | HEB 220 | HEB 200 | HEB 280 | HEB 220 | HEM 300 | HEB 300 |
| 2 | HEB 220 | HEB 200 | HEB 280 | HEB 220 | HEM 300 | HEB 300 |
| 3 | - | - | HEB 220 | HEB 200 | HEM 280 | HEB 260 |
| 4 | - | - | HEB 220 | HEB 200 | HEM 280 | HEB 260 |
| 5 | - | - | - | - | HEB 280 | HEB 220 |
| 6 | - | - | - | - | HEB 280 | HEB 220 |
| 7 | - | - | - | - | HEB 220 | HEB 200 |
| 8 | - | - | - | - | HEB 220 | HEB 200 |

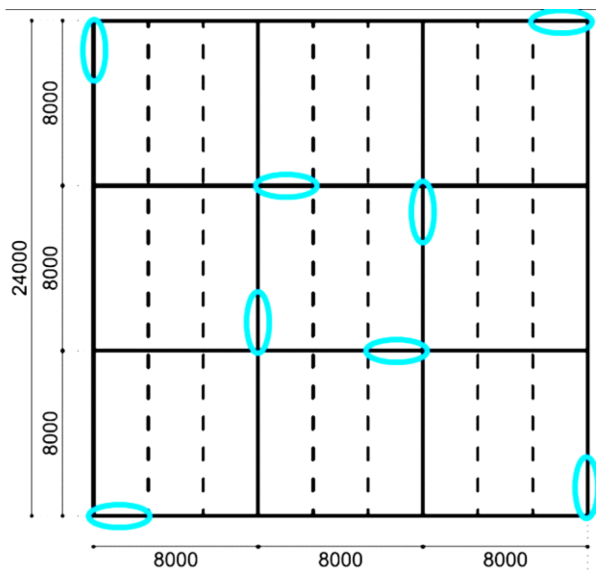
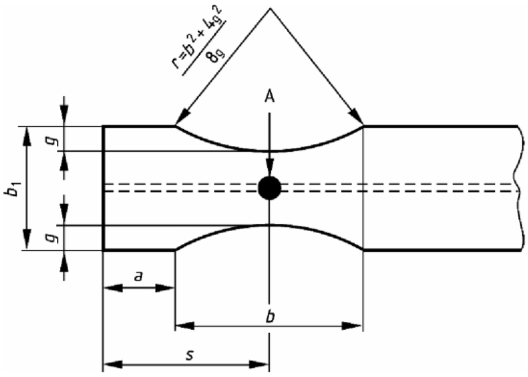



**Figure 12: Layout and position of FUSEIS beam link systems**

### 4.2 Design equations for seismic design of case studies

For the FUSEIS beam links a S235 steel has been used, weaker than the S355 steel used for all other steel parts. This makes capacity design much easier and ensures the plastic mechanism taking place in the FUSEIS beam link. For this reason, moreover, reduced beam sections have been used and the geometrical properties according to Eurocode 8-3 have been applied for the radial cuts (see Figure 13). In the numerical model used for design verification the reduced beam section properties – reduced plastic moment and reduced stiffness – have been taken into account.




| Parameter | EC 8-3 |
|---|---|
| a | $0.6 \cdot bf$ (flange width) |
| b | $0.75 \cdot d_b$ (beam depth) |
| g | $\approx 0.20 \cdot b_f < 0.25 \cdot b_f$ |
| r | $\frac{4 \cdot c^2 + b^2}{8 \cdot c}$ |

**Figure 13: Geometrical properties for reduced beam sections according to EC 8-3 [5]**

A numerical model in the design software RSTAB [7] has been setup (see Figure 15). In general design checks according Eurocode 3 [3] have been conducted regarding strength of cross sections and also stability criteria. P-Δ effects have been taken into account for all design checks. Configurations meeting the Eurocode 3 criteria, have been further checked by Eurocode 8 criteria. A behaviour factor q equal to 5 has been applied, which was found to be a reasonable value for the FUSEIS beam link system in past research [1]. The design response spectrum for soil class C, type I spectrum and a peak ground acceleration $a_g$ of 0.2g, importance class factor $\gamma_I$ of 1.0 have been applied. The design has been conducted by the modal response spectrum analysis, taking into account all relevant modes with a modal participation factor larger than 5%. Figure 14 summarizes the most important geometrical characteristics which are governing strength and stiffness of the FUSEIS beam link system.

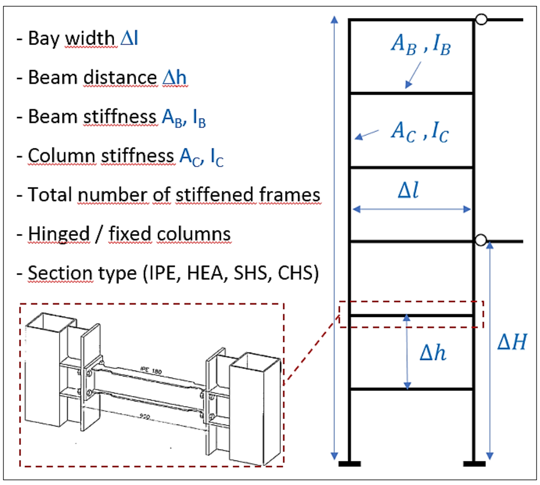



**Figure 14: Main design parameters for FUSEIS beam link system**

## 4.3 Final design outcome

Taking all design equations resulting from EC 3 and EC 8 into account, the final design of the case studies yields in the cross sections listed in the following tables. The concept of variable cross sections over different stories (see Figure 3) has been applied, in order to decrease the column size of the FUSEIS beam link system strong columns. Five FUSEIS beam links have been used per storey. The final design has been achieved iteratively, until all design equations have been fulfilled.

**Table 2: Final cross sections for seismic design of all three case studies**

| | Low-rise | Medium-rise | High-rise |
|---|---|---|---|
| FUSEIS strong columns | HEB 300 | HEB 320 | HEB 400 |
| FUSEIS bay width | 2.10 m | 2.32 m | 2.50 m |
| FUSEIS beam link length | 1.80 m | 2.00 m | 2.10 m |
| FUSEIS beam links per storey: | | | |
| 1 | HEA 220 | HEA 260 | HEA 260 |
| 2 | HEA 200 | HEA 220 | HEA 240 |
| 3 | - | HEA 200 | HEA 220 |
| 4 | - | HEA 180 | HEA 220 |
| 5 | - | - | HEA 220 |
| 6 | - | - | HEA 200 |
| 7 | - | - | HEA 200 |
| 8 | - | - | HEA 200 |

Main dynamic properties of all three final designs are summarized in Table 3, which are the periods and mass participation factors for the relevant modes. Exemplarily, the final mid-rise building is shown in Figure 15.

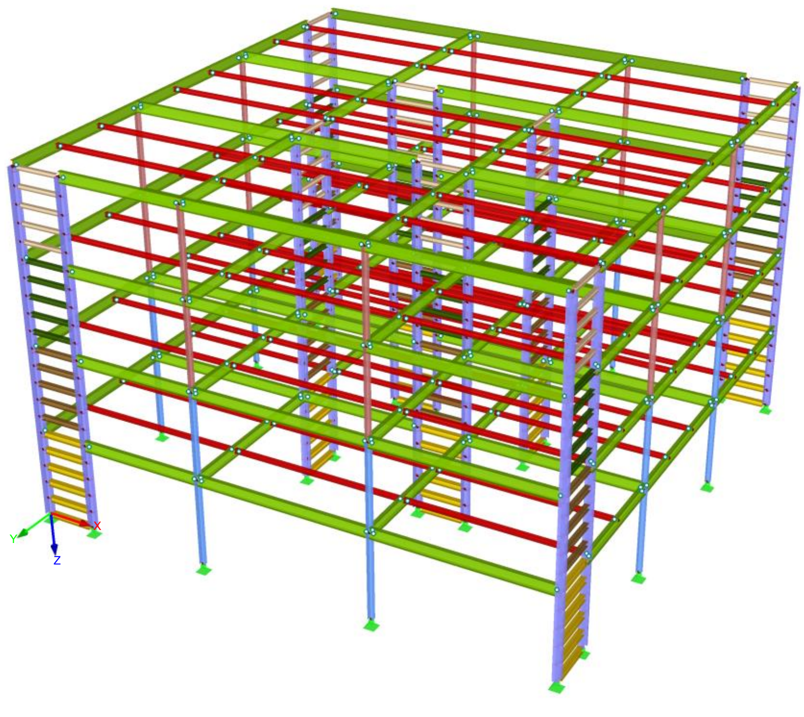



**Figure 15: Numerical model of mid-rise steel frame equipped with FUSEIS beam link system**

**Table 3: Dynamic properties of case studies**

| **Low-rise building** | F [Hz] | T [s] | $M_{eff,x}$ [%] | $M_{eff,y}$ [%] |
|---|---|---|---|---|
| 1st global sway mode X-direction | 3.28 | 0.30 | 96.5 | 0.0 |
| 1st global sway mode Y-direction | 3.21 | 0.31 | 0.0 | 95.8 |

| **Mid-rise building** | F [Hz] | T [s] | $M_{eff,x}$ [%] | $M_{eff,y}$ [%] |
|---|---|---|---|---|
| 1st global sway mode X-direction | 1.93 | 0.52 | 87.7 | 0.4 |
| 1st global sway mode Y-direction | 1.90 | 0.53 | 0.4 | 87.5 |
| 2nd global sway mode X-direction | 5.48 | 0.18 | 9.5 | 0.0 |
| 2nd global sway mode Y-direction | 5.17 | 0.19 | 0.0 | 5.1 |

| **High-rise building** | F [Hz] | T [s] | $M_{eff,x}$ [%] | $M_{eff,y}$ [%] |
|---|---|---|---|---|
| 1st global sway mode X-direction | 1.09 | 0.92 | 75.2 | 7.9 |
| 1st global sway mode Y-direction | 1.08 | 0.93 | 76.4 | 7.7 |
| 2nd global sway mode X-direction | 3.20 | 0.31 | 11.9 | 0.0 |
| 2nd global sway mode Y-direction | 3.05 | 0.33 | 0.0 | 9.0 |

## 5 CONCLUSIONS

In this paper the FUSEIS beam link system has been introduced and explained in detail. Further on, experimental tests conducted during two European research projects have been summarized. Hereby the FUSEIS beam link system showed to have stable hysteretic behaviour with high ductility and energy dissipation capabilities. The main governing design equations have been highlighted during the design of three exemplary case studies. Due to its versatility the FUSEIS beam link system can be applied for different structures and varying demands.

## 6 ACKNOWLEDGEMENTS

The presented work has been conducted in the framework of the European Research Projects FUSEIS (“Dissipative Devices for Seismic Resistant Steel Frames”) [1], MATCH (“Material Choice for Seismic Resistant Structures”) [2] and INNOSEIS (“Valorization of innovative anti-seismic devices”). The financial contribution of the Research Fund for Coal and Steel of the European Community is greatly acknowledged.

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