# SEISMIC BEHAVIOUR FACTOR IN COMBINED FRAME AND BRACED STRUCTURES

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## INTRODUCTION

In seismic design of light steel structures according to Eurocode 8 [1] the behaviour factor is accounting for the ability of the structure to dissipate energy by yielding. Applying dissipative design, cross sectional class, joint detailing and management of possible overstrength of material enable behaviour factors up to 8. Thereby, proper choice of the behaviour factor depends on the bracing system, in which all bracing elements which restrain the structure in the same direction should go plastic at the same time. This rule can be fulfilled with buildings where identical braces are in parallel walls, which provide equal stiffness and equal strength.

However, e.g. in plant construction type and position of the braces often need to be irregular due to operational reasons, see Fig.1. So the use of only one type of bracing system does not fulfil the special demands and bracing systems have to be mixed.

*Figure 1.* Gluing station for OSB-board production under construction (courtesy of Dieffenbacher 2005)

The common engineering practice would imply to calculate on the safe side and thus using the lower behaviour factor. Large jumps of the values of the behaviour factors as well as the “black or white” classification leave little space left for the designer because this might alter the seismic loads on the structure by a factor of 2. A more sensitive approach might be a linear interpolation between the corresponding behaviour factors depending on the percentage of the bracing system of the whole structure in one main direction.

# 1 GENERAL

## 1.1 Structural regularity in Eurocode 8 [1]

In Chapter 4.2.3 of Eurocode 8 [1] the criteria for structural regularity are described. The structural regularity appears in plan (horizontal direction) or in elevation (vertical direction). Herein, buildings can be structured either regular or non-regular. Beneath the value of the behaviour factor q, structural regularity has also influence on the structural model and the method of analysis, see Table 1.

*Table 1.* Extract from Eurocode 8 [1] Table 4.1: Consequences of structural regularity on seismic analysis and design

| Regularity | | Allowed Simplification | | Behaviour factor |
|---|---|---|---|---|
| Plan | Elevation | Model | Linear-elastic Analysis | (for linear analysis) |
| Yes | Yes | Planar | Lateral force* | Reference value |
| Yes | No | Planar | Modal | Decreased value |
| No | Yes | Spatial** | Lateral force* | Reference value |
| No | No | Spatial | Modal | Decreased value |

* If the condition of 4.3.3.2.1(2)a) is also met.

** Under the specific conditions given in 4.3.3.1(8) a separate planar model may be used in each horizontal direction, according to 4.3.3.1(8).

In the further remarks of Eurocode 8 [1] criteria for regularity in plan and criteria for regularity in elevation are given. In the following the main focus is laid on the vertical direction, thus regularity in elevation. Amongst others, the following conditions must be met [1]:

*"(1) All lateral load resisting systems, like cores, structural walls or frames, run without interruption from their foundations to the top of the building or, if setbacks at different heights are present, to the top of the relevant zone of the building.*

*(2) Both the lateral stiffness and the mass of the individual storeys remain constant or reduce gradually, without abrupt changes, from the base to the top."*

If these conditions are not fulfilled a reduced value of the behavior factor has to be used.

In chapter 6 *"Specific rules for steel buildings"* of Eurocode 8 [1], Table 6.2 gives "reference values of behaviour factors for systems regular in elevation", see Table 2. These values have to be reduced by 20% if the above-named conditions for structural regularity are not met. However, it is not mentioned which behaviour factor is valid for systems with mixed bracing systems.

## 1.2 Structural regularity in practice

In practice where type and position of the braces often need to be irregular one would calculate on the safe side and thus take the lowest corresponding behaviour factor q. A more sensitive approach might be a linear interpolation between the corresponding behaviour factors depending on the percentage of the bracing system of the whole structure [3] which counts for the energy dissipation capacity, see Fig. 2.

# 2 NUMERICAL STUDY

## 2.1 General

This paper reports on a numerical study. The analyses are carried out with ANSYS (Mechanical ADPL version 5.3). Detailed information on the numerical analyses is given in Knoedel 2014 [8].

*Table 2.* Extract from Eurocode 8 [1]: Table 6.2: Reference values of behaviour factors for systems regular in elevation

| STRUCTURAL TYPE | Ductility Class | |
|---|---|---|
| | DCM | DCH |
| a) Moment resisting frames | 4 | $5\alpha_u/\alpha_1$ |
| b) Frame with concentric brancings<br>Diagonal bracings<br>V-bracings | <br>4<br>2 | <br>4<br>2,5 |
| c) Frame with eccentric bracings | 4 | $5\alpha_u/\alpha_1$ |
| d) Inverted pendulum | 2 | $2\alpha_u/\alpha_1$ |
| e) Structures with concrete cores or concrete walls | See section 5 | |
| f) Moment resisting frame with concentric bracing | 4 | $4\alpha_u/\alpha_1$ |
| g) Moment resisting frames with infills<br>Unconnected concrete or masonry infills, in contact with the frame | 2 | 2 |
| Connected reinforced concrete infills | See section 7 | |
| Infills isolated from moment frame (see moment frames) | 4 | $5\alpha_u/\alpha_1$ |

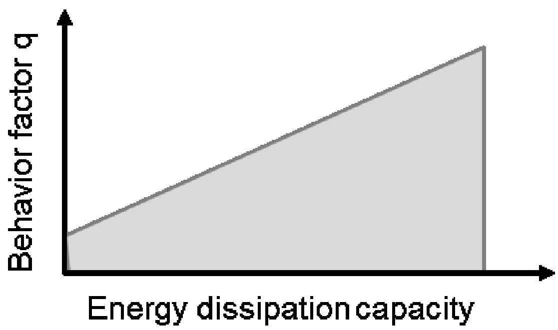


*Fig. 2.* Linear approach of the behaviour factor q in mixed bracing systems [3]

## 2.2 Frame configuration

A two column plane sway frame with 1 to 5 storeys and pinned column bases is used for the numerical investigations. Each storey has a width of 6 m, a height of 4 m according to an example given by Çeltikçi et al. [2] which was used in a previous paper by Knoedel/Hrabowski 2012 [7]. Tubular columns 400x12 mm and tubular walers 400x12 mm were taken as basic configuration. With tubes it seemed simpler to adjust the cross sections (BRBs – buckling restrained braces) by two arbitrary parameters rather than with IP oder HE sections. Following the rules of EC8 eq. 4.10 the base shear was distributed according to the storeys mass and their individual height. With an equal distributed mass of 160 metric tons per storey the seismic horizontal loads are

1/2 – 2/3 for two-storey structures
1/6 – 2/6 – 3/6 for three-storey structures
1/15 – 2/15 – 3/15 – 4/15 – 5/15 for five-storey structures.

This load configuration was used to adjust the cross sections such that plastic action would occur in all storeys within 10 % of a given base shear. The elastic limit horizontal displacement $x_{top,lim}$ of the top waler was determined for a load where first yield occurred somewhere in the structure.

For the V-braced frames the diagonals were just added to the frame without altering the sections which were originally designed for bending action. As well, no hinges were modelled for simplicity.

### 2.3 Natural frequency and driving period

The dynamical properties of the numerical model were tested and verified by means of different runs: A system under static self-weight acting horizontal was analysed at first to estimate the natural cantilever frequency by use of a simplified *Rayleigh-Morleigh* procedure.

$$f = 1/(2\pi) * \sqrt{(g / x_{top,lim})} \qquad (1)$$

A more accurate natural frequency was then determined by applying a step base displacement with a time-history analysis and determining the actual length of about 15 periods by interpolating the zero crossings (decay analysis).

The damping was adjusted by exciting the (elastic) structure in their fundamental frequency until steady-state response was found. 5 % damping corresponds to an amplification factor of (see eq. 19 in Knoedel/Hrabowski (2012) [7])

$$V = x_{response} / x_{drive} = 1 / 2D = 1 / 2*0{,}05 = 10 \qquad (2)$$

In this study we were not referring to realistic seismic base accelerations but rather derived the driving amplitude from the structural properties. We used twice the elastic limit horizontal displacement $x_{top,lim}$ and alternatively 4-fold $x_{top,lim}$. This is reflecting vice versa the design of a structure where you reduce the actual seismic movements by a behaviour factor of 2 or 4, depending on which category of bracing the structure has. With these reduced seismic actions the structure is designed (by hand) to a elastic limit, or, with common rolled sections to not more than 15 % higher stress resultants. Thus a structure with a behaviour factor of 4 is expected to be able to withstand “real” base displacements which are by a factor of 4 higher than the structure is designed for.

### 2.4 Elements

A 2-D model with plastic BEAM23-elements is the basis for the analysis.

The element size is chosen in a range of 0,2 m to 0,5 m, i.e. 6 to 30 elements per member, which proved to be sufficient for the present analysis [8].

### 2.5 Material

As material law a simplified bi-linear constitutive law with isotropic hardening is chosen for steel with Young’s modulus of 2,1 GPa up to a yield limit of 235 MPa. Above that a straight line to the ultimate tensile stress 360 MPa at assumed 20 % strain is used. Thus an ‘engineering plastic modulus’ with a slope of

$$\Delta\sigma / \Delta\varepsilon = (360 \text{ MPa} - 235 \text{ MPa}) / 0{,}2 = 625 \text{ MPa} \qquad (3)$$

can be received. This approach has been used before, see eq. 15 in [7].

### 2.6 Time-History Analysis

For the presented analyses the transient dynamic analysis was performed such that 15 to 20 load steps were used within a period. Between these major steps automatic time stepping was used, which results in up to 100 sub steps in between.

As described in an earlier paper the drive is switched off after 10 periods [7], which does not quite meet the demands of EC8 but does not influence the results of the structural behaviour under investigation.

### 2.7 Behaviour factor

Per definition the behaviour factor q is the relation of the amplitudes of an (taken as) elastic structure and the actual structure including dissipation by plasticity.

The analysis of the elastic response (accounting for 5 % structural damping) is described above. The behaviour factor was determined by taking the maximum amplitude which occurred within a 10 periods drive.

### 2.8 Results

*Table 3.* Numerical results with mixed bracing systems

| Model no. | q (q=2) | q (q=4) | no. storeys | no. frames | no. Vs |
|---|---|---|---|---|---|
| 8 | -- | 14,1 | 5 | 5 | 0 |
| 9 | 6,3 | -- | 5 | 0 | 5 |
| 10 | 5,4 | 13,6 | 2 | 2 | 0 |
| 11 | 7,6 | 11,2 | 2 | 0 | 2 |
| 12 | 10,8 | 8,4 | 2 | 1 | 1 |
| 13 | 6,7 | 8,4 | 2 | 1 | 1 |
| 14 | 5,9 | 14,3 | 3 | 3 | 0 |
| 15 | 4,9 | 10,0 | 3 | 2 | 1 |
| 16 | 6,4 | 6,1 | 3 | 1 | 2 |
| 17 | 7,5 | 11,0 | 3 | 0 | 3 |
| 18 | 6,7 | 9,5 | 3 | 1 | 2 |
| 19 | 5,8 | 10,9 | 3 | 2 | 1 |
| 20 | 7,4 | 10,5 | 3 | 1 | 2 |
| 21 | 6,4 | 8,6 | 3 | 2 | 1 |
| 22 | 6,2 | 7,9 | 1 | 1 | 0 |
| 23 | 5,9 | 8,3 | 5 | 5 | 0 |
| 24 | 7,2 | 10,8 | 1 | 0 | 1 |

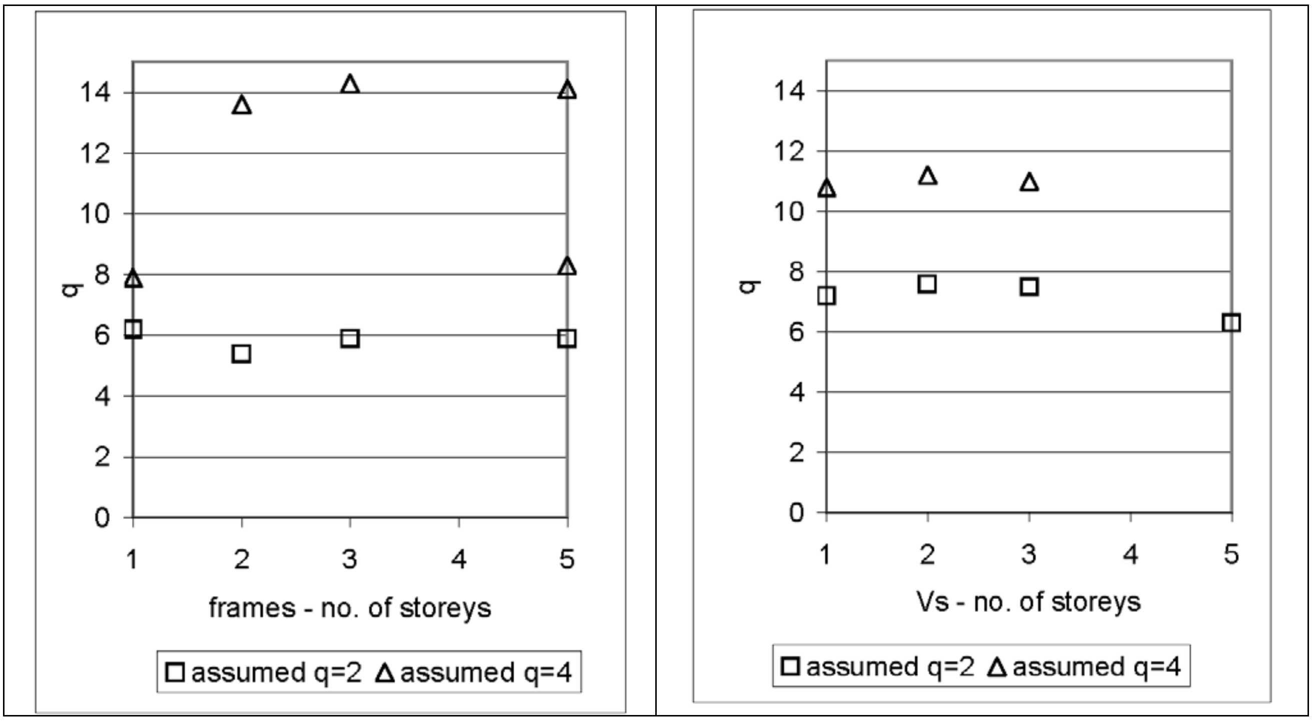


*Fig. 3.* Behaviour factors for multi-storey non-mixed structures – frames (left), V-braces (right)

## 3 INTERPRETATION AND CONCLUSIONS

- The behaviour factors given for frames in EC8 seem to be very conservative, instead of 4 we found values around 6. This might account implicitly for structures with low utilisation, which have a reduced behaviour factor as was discussed in Knoedel/Hrabowski 2012 [7].

- Assuming a higher behaviour factor – and thus increasing the driving amplitude – will result in an even higher behaviour factor, we found factors 14 for frames. If you double the driving amplitude the response of the structure will not double due to plastic action. Limits might be found in an realistic push-over analysis including second order effects, which we excluded to reduce the number of parameters in this study.

- For V-braces we found behaviour factors of even more than 6 when we assumed 2. So far the background of the above table 6.2 from EC8 is not quite clear.

- We had no trouble in using four times the elastic limit amplitude on the V-braces but their capability of increasing behaviour factors seems to be limited compared to frames. We found behaviour factors of 11 instead of 14 with frames.

- Since pure frames and V-braces showed about the same behaviour factors it is obsolete to give a more specific rule for mixing than the general assumption in Fig. 2.

- The evolution group of EC8 should consider an informative annex where rules are given for simple determination of behaviour factors. From our experience this is very helpful before going into "real big" analyses with non-harmonic base excitation. For a comparison of "hand" vs. advanced methods see Knödel/Heß 2011 [7].

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