Full-scale tests on steel frames under cyclic loading

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Abstract. An experimental investigation on full-scale frames aimed at determining the effect of flexibly in the beam-column connections with cycling loading is described. The paper presents an overview of the experimental set-up and briefly explains how the complexities arising from the three-dimensional nature of the tests were addressed. The quality of the collected experimental data has justified the effect, which was expended in addressing the experimental complexities.

1. Introduction

The structure of a building can be supplied by different types of loads and environmental impacts. In practice the loading of a structure is modeled as a continuously increasing, quasi-static system. On the other hand temporary aspects of different environmental impacts and loads should also be investigated, since meteorological loads (snow, wind, and temperature change) cannot be modeled as continuously increasing system. In the experiments beside the increasing vertical force, an alternating horizontal force or pulsating force was also applied. Due to the effect of these different loading types the behavior and response of structures can also be quite different. For example plastic states develop which in the case of repetitive loading will result in a hysteretic behavior in structures.

Semi-continuous framing, i.e. framing in which partial strength and semi-rigid joints according to the Eurocode 3 [1] definitions are applied, is gaining importance in building structures due to the economy offered and the possibilities for modeling and calculation provided by a new set of design codes [2]. The connection models presented in these design standards and in the technical literature in general are based on the enormous number of tests, experimental and numerical, which were performed in the last decade or two (see e.g. [3]), most of them examining joints isolated from the whole structure in which they are to be incorporated. However, it is not evident how these joints behave when they become part of a real frame; it is recognized that this problem needs experimental investigations performed on full-scale frames and realistic solutions for connection behavior.

A series of tests in 1993/94 consisting of four, two-storey and two-bay frames [4], in which partial strength and semi-rigid joints were applied for column bases as well as beam-to-column connections. However, these joints were not designed to accommodate plastic hinges; therefore the failure of the frames in all instances was due either to loss of member stability or to connection failure in a brittle manner.

The new test series presented in this paper consists of frames prepared with semi-rigid beam-to-column joints where special attention was devoted to the detailing of these joints in order to ensure a rotation capacity sufficient for a plastic mechanism to occur within the frame. Furthermore, the tests
concentrated mostly on the behavior of these frames under quasi-static cyclic loading with different types of load histories. These way two objectives were set at the start of the tests: (i) to examine the behavior of the frame itself under the circumstances covered, and (ii) to look at the behavior of the partial strength and semi-rigid connections within these frames.

2. Testing program

2.1. Structure

The experimental research project was carried out in the Laboratory of the Department of Bridges and Structures, Budapest University of Technology and Economics. In figure 1 there is the general view of the experimental test frame.

![General view of experimental test frame.](image)

An overall view of the testing arrangement is shown in figure 2. The frames examined are two-storey single-bay ones. Both the columns and the beams are welded I sections, see table 1. Pairs of test frames are identical. Columns are connected to a rigid steel base element by two bolts through an end plate (layout generally regarded as pinned joint in the practice).

Beams and columns are connected with flush end plate joints (figure 3). In OTKA frames 1 to 5, the connections are strengthened with single-sided additional web plates. These were found to be necessary on the basis of an analysis of joint behavior according to Eurocode 3 Part 1.8. [5] According to the predictions, the joints were to fail in their tension zone, by Mode 1 bending of the end plate, a failure mode generally recognized as one ensuring sufficient rotation capacity to accommodate a plastic hinge within the connection. These predictions also showed that omitting the additional web plates would have caused column web buckling to become the governing failure mode, which is regarded to be ineffective in terms of plastic hinge behavior. Despite these predictions, joints in...
OTKA frame 6, in which these plates were indeed omitted, showed similarly ductile behavior as those in OTKA frames 1 to 5.

![Diagram of tested frames](image)

**Figure 2.** The tested frames: (a) main geometry and (b) lateral restraints.

**Table 1.** Beam and column sections applied in the tests.

| Frame | Beam (flange/web) | Column (flange/web) |
|-------|-------------------|---------------------|
| 1, 2  | 130-8/260-8       | 200-12/260-8        |
| 3, 4  | 160-10/260-8      | 200-12/260-8        |
| 5, 6  | 130-8/260-8       | 160-10/260-8        |

In addition, these joints showed a type of asymmetric behavior which, according to the best knowledge of the authors, is not treated in the technical literature, and which is not covered by design code regulations. This behavior, characterized by excessive yielding of the column flange at one side and similarly excessive yielding of the end plate at the other, is due to the asymmetry of the joint because of the single-sided additional web plate, and suggests that these web plates play a more sophisticated role in the joint behavior than as implied in current European regulations. This issue is discussed in more detail elsewhere [6].

In order to avoid lateral-torsional buckling, lateral restraints are applied to the frame at the beam-to-column joint locations and at the mid-spans of the beams, see figure 2.

2.2. Loading

The frame is loaded by two vertical concentrated loads at the mid-spans of the beams, and two horizontal loads applied at one side of the frame in the levels of the beams (figure 2).

The two vertical loads are increased and decreased proportionally using three hydraulic jacks (one larger to the lower beam and two smaller and identical to the upper) connected into one oil circuit. Because of the slight difference between the pressure surfaces of the larger jack on one hand and the two smaller jacks on the other, the lower beam was loaded by a concentrated load 89% in magnitude of the load on the upper beam. The vertical loads are applied through so-called gravity load simulators [7], devices, which ensure the verticality of the loads within certain limits of lateral displacements of the points of application of the loads.
The horizontal loads are applied using one hydraulic jack through a simply supported vertical beam, which ensures the applied load, to be equally distributed between the two beam levels. The direction of these horizontal loads is reversible.

The loading histories under which test OTKA frames 1 to 6 were examined are shown in table 2 and figure 4. OTKA frame 1 was loaded by proportionally increasing loads; OTKA frames 2 to 6 were loaded by increasing vertical loading and cyclic horizontal loading at the levels of the vertical loads. In the case of OTKA frames 2, 3, 5 and 6, the amplitude of the horizontal loads was set as a ratio of the vertical loads, while in the case of frame 4, this amplitude was set to a constant value. In the case of all frames except OTKA frame 4, the ratio of the vertical loads and horizontal loads was set to 1:6 (value of one horizontal force as compared to the vertical load acting on the upper beam); for OTKA frame 4, the amplitude of the horizontal load cycles was set to a constant value of 36 kN (value of one horizontal force).

**Table 2.** Loading program.

| Frame | Program description | Highest vertical load (kN) |
|-------|---------------------|---------------------------|
| 1     | monotonic monotonic | 193.4                     |
| 2     | monotonic cyclic    | 208                       |
| 3     | monotonic cyclic    | 240                       |
| 4     | monotonic cyclic    | 240                       |
| 5     | monotonic cyclic    | 196                       |
| 6     | monotonic cyclic    | 200                       |
Figure 4. Loading program, (a) general program in terms of vertical forces for OTKA frames 2 to 6 (columns represent cycles of horizontal loads); (b) vertical force versus horizontal force for OTKA frame 2 as measured.

3. Measurements

During the tests we measured beam mid-span deflections and lateral storey displacements by using inductive transducers, forces by pressure transducers built into the oil circuit of the hydraulic system, strains by strain gauges and cross-section rotations by purpose-designed devices (figure 5).

The strain measurement was taken at the end cross-sections of beams and columns, by using ten gauges for each cross-section. The arrangement we applied was first used by [8], and makes possible to derive the four cross-sectional internal forces (the axial force, the two bending moments and the bimoment) even in the case of plasticity occurring within a part of the cross-section (figure 6). We did not, however, expect excessive plasticity in these cross-sections due to the fact that the beams and columns were connected by partial strength connections.

We applied a special purpose-designed device referred to as rotation indicator for the measurement of the absolute rotations of cross-sections (figure 7). This device consists of spring steel connected rigidly on its top to the cross-section being examined. While the cross-section and the top of the spring element rotates, a weight connected to the bottom of this spring element tries to remain in place, which causes bending within the spring steel element.
The deformations depend on the rotation to be measured, and are assessed by two strain gauges on the two surfaces of the spring steel element. The device is suitable for the measurement of rotations within the range of ±10 degrees. The device was calibrated for this range and was found to behave linearly; its coefficient, i.e. the ratio between the rotation and the difference of strains as measured by the two strain gauges, was in the range of 7.8 to 9.0 × 10⁻³ degrees per micro-strains (the results come from the calibration of the fifteen rotation indicators constructed).

Material properties of the applied steel was determined on the basis of tension tests, see table 3.

| Plate element | Yield strength (MPa) | Ultimate strength (MPa) |
|---------------|----------------------|-------------------------|
| Thickness     | Purpose              |                         |
| 8 mm          | web, flange          | 300                     | 429                     |
| 10 mm         | flange               | 276                     | 384                     |
| 10 mm         | end plate            | 320                     | 444                     |
| 12 mm         | flange               | 274                     | 382                     |
Figure 7. The rotation indicator. The ‘weight’ element is a $\phi 50 \times 67$ solid element; the ‘spring’ element is a $0.5 \times 34 \times 40$ steel element, with a cross-section weakened to 7 mm$^2$ at the strain gauges.

4. Results of OTKA-1 with proportional loads

The frames examined are two-storey single-bay ones. Both the columns and the beams are welded I sections. Pairs of test frames are identical. Columns are connected to a rigid steel base element by two bolts through an end plate (layout generally regarded as pinned joint in the practice).

Beams and columns are connected with flush end plate joints. In frame OTKA-1, the connections are strengthened with single-sided additional web plates. These were found to be necessary on the basis of an analysis of joint behavior according to [5].

The frame is loaded by two vertical concentrated loads at the mid-spans of the beams, and two horizontal loads applied at one side of the frame in the levels of the beams. The two vertical loads are increased and decreased proportionally using three hydraulic jacks (one larger to the lower beam and two smaller and identical to the upper) connected into one oil circuit. Because of the slight difference between the pressure surfaces of the larger jack on one hand and the two smaller jacks on the other, the lower beam was loaded by a concentrated load 89% in magnitude of the load on the upper beam. The vertical loads are applied through so-called gravity load simulators, devices which ensure the verticality of the loads within certain limits of lateral displacements of the points of application of the loads. The horizontal loads are applied using one hydraulic jack through a simply supported vertical beam, which ensures the applied load to be equally distributed between the two beam levels. The direction of these horizontal loads is reversible.

Concerning the experimental frame OTKA-1, the relation of load-deflection curve develops according to figure 8. The Approximate Engineering Method is presented on test frame OTKA-1 (figure 8) [9]. The comparison shows that the Approximate Engineering Method gives satisfactory results for the maximum loads and the descending state path of whole structure as well; and at the same time the analysis can be done at the ‘desk of the designer’.
5. Results of OTKA 2-6 with cyclic loadings

The ultimate behavior of the OTKA frames was characterized by excessive yielding within the joint zones (plastic mechanism), and in the beams below the vertical loads, and the failure was in nearly all instances due to the buckling of the compression flanges of the top beams below the vertical loads, and then by the initiation of lateral-torsional buckling in the top beams.

In OTKA frames 2 to 6 the cross sections for beams and columns were different, see table 1. The loading program were different too, see table 2. Figures 9-13 have shown the similar load vs. displacement and rotation curves for OTKA frames 2 to 6. In the figures there are some details of experimental results:

(a1) Vertical load of upper beam versus top storey drift
(a2) Total horizontal load versus top storey drift
(b1) Vertical load of upper beam versus vertical deflection
(b2) Total horizontal load versus vertical deflection
(c1) Vertical load of upper beam versus rotation at ‘0’
(c2) Total horizontal load versus rotation of section ‘0’
(d1) Vertical load of upper beam versus normal force at ‘2’
(d2) Total horizontal load versus normal force at section ‘2’.

6. Conclusion

The paper sets the objective to present the testing methods applied during a test series consisting of six frames with similar geometry and, in five cases, under quasi-static cyclic loading. The testing methods presented in the paper prove to be suitable for the given purpose. Special attention is paid to a device, a new development, referred to as rotation indicator, which has been constructed to measure the rotations of cross-sections.

Further work related to these tests will concentrate on the detailed analysis of the results collected. The focus will be to look at the connection behavior, which in one sense is peculiar due to its asymmetry relative to the plane of the frame, and which will also be interesting from the point of view.
Figure 9. Load vs. displacement and rotation curves for OTKA frame 2.
Figure 10. Load vs. displacement and rotation curves for OTKA frame 3.
Figure 11. Load vs. displacement and rotation curves for OTKA frame 4.
Figure 12. Load vs. displacement and rotation curves for OTKA frame 5
Figure 13. Load vs. displacement and rotation curves for OTKA frame 6.
of the information available about behavior of connections tested off-frame. Another main direction of
the further assessment of results will concentrate on the behavior of the frame as a whole.

In the traditional (standard) load bearing capacity analysis the ultimate limit state is investigated
under continuously increasing loading. The shakedown state is also usually analyzed under alternating
and pulsating horizontal loading. Although these analyses correspond to the load bearing capacity, it is
also important to investigate the process, which leads to this ultimate state, therefore it is necessary to
investigate the hysteretic behavior of structures. The presented experimental results can provide good
bases for further theoretical and numerical investigations.

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