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Destructive testing of full-scale engineering structures as an excellent source of knowledge

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Abstract

The main aim of this paper is to present how informative, and relevant in advancing the current state of knowledge, destructive experiments can be, particularly when carried out in a controlled manner on full-scale objects. All the considerations presented in the manuscript are based on the results of the experiments that were fully devoted to the observation of the lattice telecommunication towers under breaking load. During the tests, measurements of the particular, important parameters have been taken, namely strains of structural members obtained via strain gauges, the displacements of the observed nodes and, last but not least, the failure mechanism and failure modes registered by the video cameras placed externally and internally to the structure. Conducting full-scale tests, although particularly difficult, laborious and, most of all, costly, cannot be overstated enough. The executed operation showed without any doubt that the failure mechanism observation of the full-scale structures allows for calibration of numerical models, reliability assumptions, and justified correction of standard descriptions.

Keywords: telecommunication structures, lattice towers, full-scale experiments, failure mechanism, failure mode, plastic deformations, buckling

1. Introduction

Behavior of structures under breaking load is undeniably among the research targets for the civil engineers. Both analytical descriptions and computer-based analyses of varying complexities are used to investigate the phenomenon. Nevertheless, taking into consideration the number of assumptions or simplifications behind any of the analyses, the best way to obtain the real structure response are undoubtedly the full-scale tests.

Full-scale tests provided useful data to the research areas of steel, concrete or timber structures which seems to be already under active development. While experiments on full-scale engineering constructions produce results which are not easily obtained, they are difficult to realize due to destruction of research subjects, realization in appropriate terrain which has to be adapted, use of suitable measurement instruments, or purely financial reasons. However, the data from these experiments may serve the modification of construction behavior and later works involving modeling, optimization, etc. As mentioned in [3], experimental tests are frequently used as a validation procedure in development of numerical structure models. Taking engineering structures into account, their complexity level, scale, and diversity of any kind are very large making it impossible to give analytical solutions in most structural problems.

The experiment itself should be carried out taking into account several factors. All the elements that should be considered before, during and after the test were presented in work of Birkemoe [2]. He noted that the role of experimental research is linked directly to development of specialized hardware, computer software and also analytical possibilities in civil engineering. He believes that the decisive factor for successful experiments; apart from measurements of imperfections, tension, and deflection; is supplementing the data with material properties. Geometrical properties and imperfections, and residual stresses are essential for credibility of results and subsequent conclusions. Works showing behavior of constructions under breaking load, both experimental and analytical, create new trends in solving construction problems.

Full-scale experiments have been carried out in the past with notable success. Albermani et al. in [1] used results of a study carried out on a 1:1 scale transmission tower to create a numerical model which allowed for prediction of transmission tower failure.

Lee and McClure also used a full-scale experiment [3] which consisted of a pushover test of a single, 10 meters transmission tower section consisting of angle beams with typical eccentric connections in order to depict the phenomenon of large deformations. They introduced a numerical model simulating the ultimate behavior of the structure. The numerical assumptions were verified by a comparison with the results obtained during the experiment.

Taillon et al. in [6] also contributed to static and dynamic tests of lattice structures. In their experiment, an 8 meter transmission tower was subjected to a pushover test and a sudden release of stresses in order to record its free vibrations. In conclusions, they stated that, considering the complexity of real lattice towers, it would be interesting to perform a test on a real one.

The main goal of this paper is to present how informative, and relevant in advancing the state of knowledge, destructive tests can be, particularly when carried out in a controlled manner on full-scale objects. To achieve these objectives, the results obtained for experiments involving ultimate loading of full-scale steel telecommunication towers are presented in the article.

The subject of telecommunication structures is widely elaborated and presented by Smith in [5] and Rykaluk [4].

2. Performed full-scale experiments

The experiments were carried out in November and December, 2014. A controlled destruction of a 40 m, lattice telecommunication towers was performed taking into consideration several objectives:

- identification of the failure mechanism of the tower members, with particular regard to buckling of the legs as well as capture of the diagonal bracing element behavior,
- geodetic measurement of displacements of particular tower nodes against loading force value,
- measurements of strains with electric resistance strain gauges placed on legs and diagonal bracing elements of the spatial truss,

- experimental determination of the bearing capacity of the tower, necessary for usability verification of such structures after antenna systems have been modernized, number of antennas has changed etc.
- determination of breaking force causing buckling of tower legs as defined in serial reliability system,
- and comparison of obtained results with ones calculated according to EC3 norm.

The means used in order to accomplish the goals mentioned above included measurement instruments which allowed for reading the strain gauges on the tower legs and of the load cell (which allowed for direct registration of strains and external load), geodetic measurements of structure nodes, video recording from video cameras placed internally and externally to the tower body as well as on a flying object: a drone.

The distance between the tower and the towing truck, the height of placement of the steel diaphragm, as well as points (labeled A, B, and C), which were subjected to geodetic measurements of displacements during the test, are shown in Figure 1.

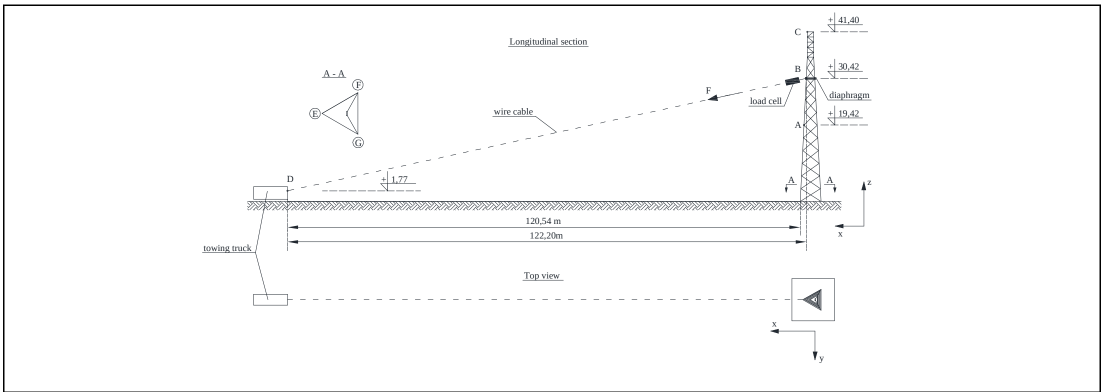


Figure 1: Scheme of the performed tests

Due to the dimensions and scale of the structures, the experiment was carried out in an area ensuring its safe completion. Works which were performed prior to research efforts may be divided into following phases:

- preparation of experiment site for heavy equipment access,
- production of a supporting frame allowing for fixing studied tower in foundation, and its loading with prefabricated concrete slabs,
- and vertical assembly and horizontal installation of the structure, production of a steel diaphragm and placing strain gauges on chosen tower elements.

A top view of the tower during the experiment, as well as the research site, are presented in Figure 2.

Figure 2: Top views of the experimental site

2.1 One of the tested structure description

The experiments were performed for two towers with triangular cross sections and heights equal to 40 meters each. The concept of structure is the same for both towers; the differences were noted only about the cross-sections of particular members. Taking the above into account, as well as the fact that this manuscript is devoted to description of the advantages that experimental studies can give, one detailed description for one of the tested towers is presented.

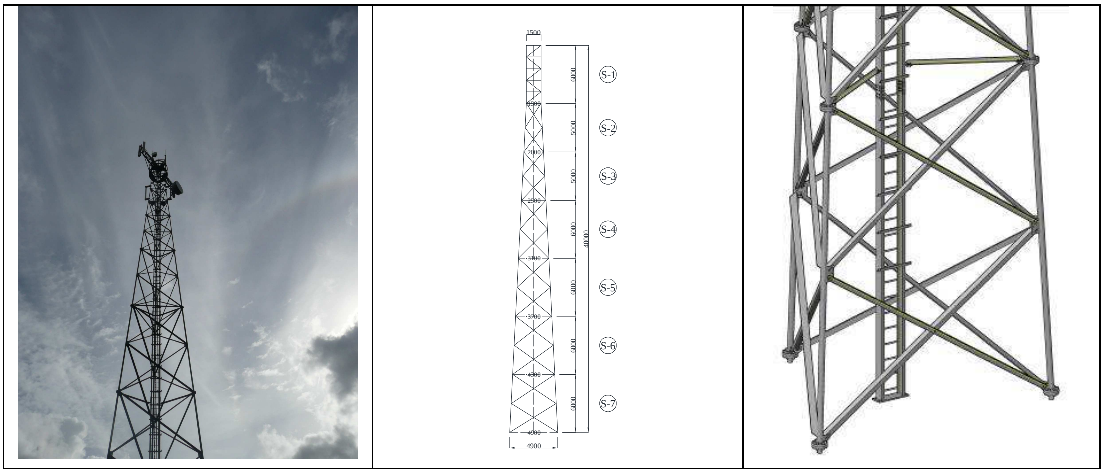


Figure 3: View of the tower in normal exploitation (left), scheme of the structure (middle), and view of section S-7 (right)

Tower body was manufactured as a three-dimensional truss of a triangular cross-section and height of 40.0 meters divided into seven sections. Its upper part is of a triangular cross-section and the bottom part (up to 34th meter) forms a pyramid frustum with constant 5% convergence. The centerline dimension is 4.90 m at its base and 1.50 m at its top. The upper part of the tower is a parallelepiped of a height equal to 6.0 m with the cross-section of an equilateral triangle of side length equal to 1.50 m. The segmentation of the tower, the heights, names of the sections, and a 3D view of bottom section S-7 with a climbing-cable ladder is shown in Figure 3 above.

The leg members in each section consist of round solid bars, and bracing elements consist of hot-rolled symmetrical and nonsymmetrical angle sections. Diagonal bracing system of the tower is of type X. The bracing elements are continuous in structure and the joints at their intersections are made with a spacer and a single bolt. Their connections with diagonal bracing of the lattice were realized with gusset plates and bolts, two for a node. The profiles of particular elements of the tower are presented in Figure 4 below.

Section	Legs	Diagonal bracings
S-1	Ø 65	∟60x60x5
S-2	Ø 65	∟60x60x5
S-3	Ø 80	∟60x60x6
S-4	Ø 80	∟90x60x8
S-5	Ø 90	∟90x60x8 ∟100x75x8
S-6	Ø 90	∟100x75x8
S-7	Ø 100	∟120x80x8

Figure 4: Selected tower element profiles, all dimensions are given in mm

To attach the legs of the tower connecting flanges and adequate number of bolts were used. Data concerning individual joints, thickness and size of the flanges, and the number and type of bolts in individual sections are presented in Figure 5.

Section	Diameter of the lower/upper flange	Thickness of the lower/upper flange	Bolts in the lower/upper flange	Number of bolts in the joint
S-1	180/180	25/25	M16x75(8.8)/M16x75(8.8)	6
S-2	180/180	25/25	M16x75(8.8)/M16x75(8.8)	6
S-3	200/180	30/25	M16x85(8.8)/M16x75(8.8)	6
S-4	220/200	30/30	M20x90 (8.8)/M16x85(8.8)	6
S-5	230/220	30/30	M20x90(8.8)/M20x90(8.8)	6
S-6	260/230	35/30	M24x105(8.8)/M20x90(8.8)	6
S-7	260/260	35/35	M24x105(8.8)/M24x105(8.8)	6

Figure 5: Data concerning legs of the tower joints of individual tower sections, all dimensions are given in mm

The tower was provided with a climbing-cable ladder. The ladder is attached to two legs at every section with bolts.

3. Results

Taking structure analysis into consideration, the results are given in short, individual, principal sections with the main reason being, as mentioned before, the presentation of research possibilities given by full-scale experiments. All the results shown significantly broaden the knowledge on behavior of slender lattice structures under ultimate load.

3.1 Failure mechanism and failure modes

The buckling of the tower legs and its destruction were captured by video cameras placed both internally and externally to the bodies of the towers. The films presenting the failure mechanisms are available online at https://www.youtube.com/channel/UCmIoOMNM2U2oNzDHoQeIgOA. It is worth noting that, for both cases, the buckling of the legs occurred perpendicularly to the loading force. Plastic hinges occurred at the centers of the bracing panels, at ¼ and ¾ of section span.

Figure 6: Failure mode of the first tested tower – view from the front (left) and the elevation (right)

Due to the fact that the towers differed at cross sections of the legs and diagonal bracing elements, buckling occurred at different heights and at different sections. Failure mode of the first tested tower is depicted in Figure 6. The attached pictures show that the main plastic deformations occurred in the compressed leg of section S-5 in case of first tested tower. The details of the deformed legs are depicted in Figure 7.

Figure 7: Buckling of tower legs in section S-5 (first test) – view from the front (left) and the base (right)

The buckled leg in the second tower is presented in Figure 8. It should be noticed that the joints connecting the neighboring legs remained rigid due to significant thickness of the connecting flanges, and no so-called leverage effect was present.

Figure 8: Buckling of tower legs in section S-7 (second test)

3.2 Plastic deformations

The test on structures, whose particular elements are real scale, used in practice, i.e., full-scale structures, allows for measurements of the plastic deformations. The advantage of those kinds of tests over the tests on laboratory models, which do not have real scale, is particularly visible in this case.

The measurements of the deformed elements are presented in a graphical form in Figure 9. The data may serve the adaptation of FEM models for damage analysis or analytical behavior descriptions of such elements under buckling load.

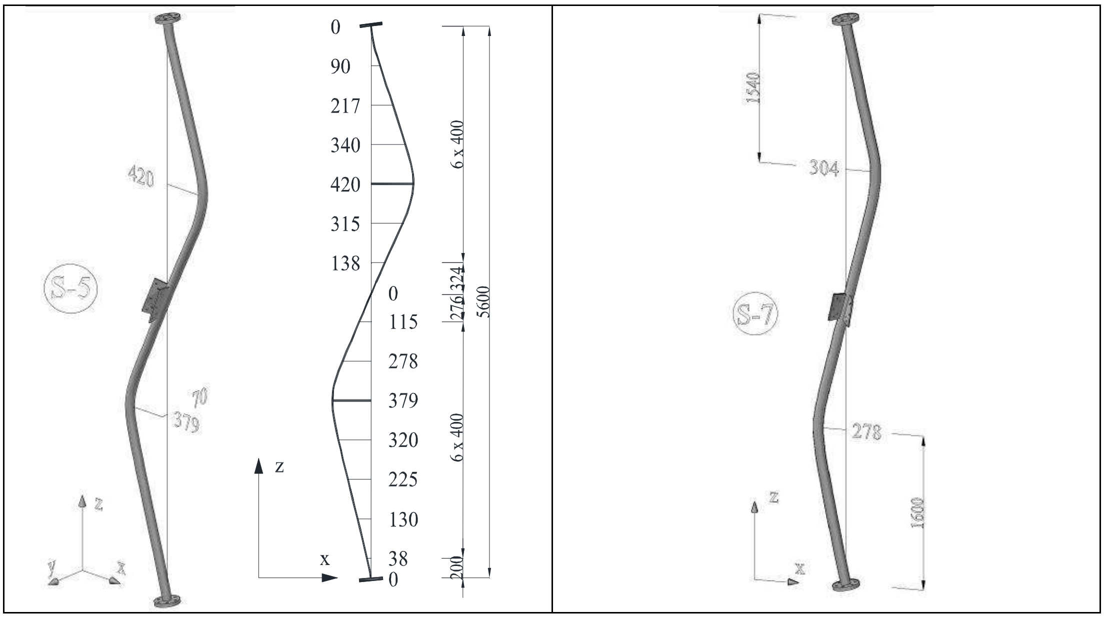


Figure 9: Plastic deformation measurements in the buckled legs

3.3 Axial forces in compression

The results presented in this subsection are taken directly from the experiment on the second tower.

The strain measurements were taken with electric resistance strain gauges and the layout of particular measuring points for section S-7 is presented in Figure 10, where the legs of the tower are presented in the following manner: leg 1 as the leg under compression during the test, leg 2 and leg 3 as the legs under tension.

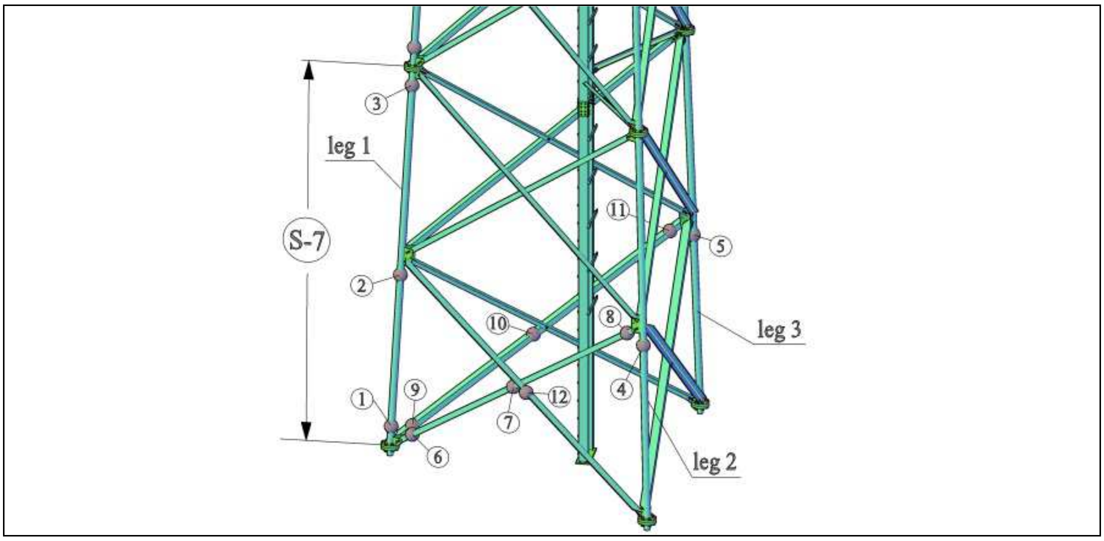
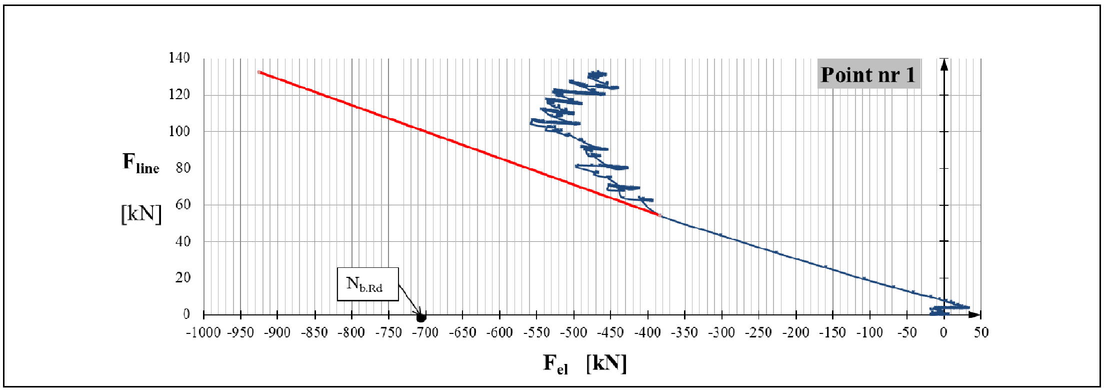


Figure 10: Arrangement of measuring points in section S-7 of the second tower

The axial forces in legs of the tower obtained by measuring points are presented in a graphical form as a function of the external load (force in the line). Internal forces were determined at the analyzed measuring points based on the arithmetic means of strain (stress) readings from particular strain gauges. Both extrapolated and experimental results have been put on the graphs. Extrapolated results were determined based on stress at chosen measuring points. This decision was dictated by the fact that relations for these points were characterized by high linearity and absence of anomalies such as unfounded high scatter of results (caused by, e.g., strain gauge damage). The values of the axial forces for the leg in section S-7 (measuring points 1-lowest, 2 - middle, and 3- highest), which was destroyed during the experiment, are shown in Figure 11.



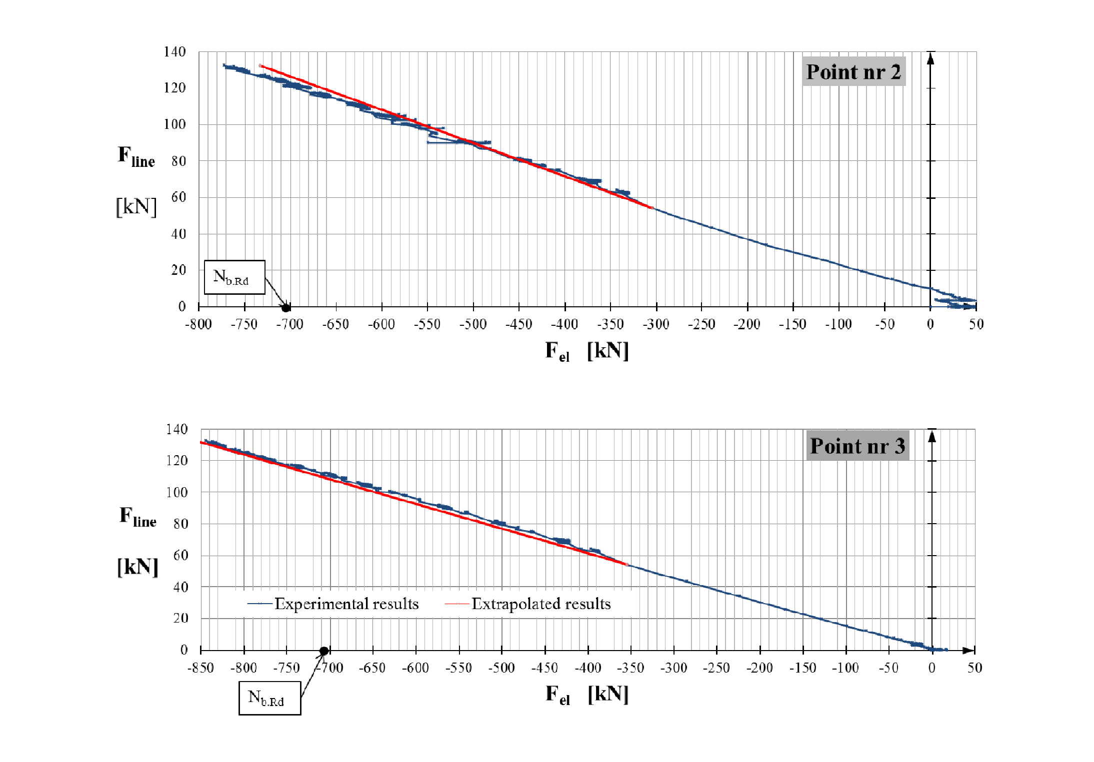


Figure 11: Axial forces in particular measuring points of the compressed leg of section S-7

The maximum value of the force in the leg amounted to -924.5 kN (minus for compression), which is also the sought value of breaking force in the leg. The value was reached for the force in line of 132.5 kN which may be assumed breaking load in case of the analyzed structure. A rather big difference between experimental and extrapolated values was noted at measuring point no 1.The variety of strains, and therefore stresses, occurred mostly at supporting node. The four strain gauges placed there showed rather high scatter of results which was probably caused by the manner of leg attachment to the supporting frame. The difference resulted from support conditions as mentioned before, and also the number of structure elements attached to the examined node.

On the graphs there are presented standard buckling resistance $N_{b,Rd}$ calculated according to the standard Eurocode 3: Design of steel structures – Part 3-1: Towers, masts and chimneys – Towers and masts. Is worth underlining that, for the analyzed case, the experimental member buckling capacities are notably greater than standard buckling resistance.

4. Conclusions

The selected results of research efforts on steel telecommunication towers have been presented. The aim of the presentation was to show how difficult the task of full-scale experiments is and how much results may be obtained this way. Another fact worth mentioning is that structure response, in the form of stresses or failure modes, is of great significance. The main conclusions, which stem from the tests and the above considerations, are:

- the performed experiments extend the current state of knowledge on high lattice structures in a particular way, due to the fact that the research was based on a full-scale structure in compliance with all the structural details and preserving its complexity without any simplifications which characterize laboratory test on structural models,
- the failure mechanics of the structures has been revealed in both analyzed cases,
- the axial forces in the particular structural members were measured and can be compared to the ones obtained via standard procedures,
- the plastic deformations measurements as well as the failure modes can serve as benchmarks for complex numerical analyses.

In opinion of the author of this manuscript, full-scale experiments are the best way for developing the methodology of structural analysis.

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