LIGHTWEIGHT STRUCTURES in CIVIL ENGINEERING
CONTEMPORARY PROBLEMS
Monograph from Scientific Seminar
Organized by Polish Chapters of
International Association for Shell and Spatial Structures
Lodz University of Technology
Faculty of Civil Engineering, Architecture and Environmental Engineering
XXIV LSCE –2018
Łódź, 7th of December, 2018

REINFORCEMENTS OF TOWER STRUCTURES: EFFECTIVE AND ECONOMIC DESIGN ENGINEERING

J. Szafran[1] K. Juszczyk[2] M. Kamiński[3]

[1] Adjunct Professor, Chair of Structural Reliability, Department of Structural Mechanics, Faculty of Civil Engineering, Architecture and Environmental Engineering, Łódź University of Technology, Łódź, POLAND,
email: jacek.szafran@p.lodz.pl

[2] M.Sc. Eng, Chair of Structural Reliability, Department of Structural Mechanics, Faculty of Civil Engineering, Architecture and Environmental Engineering, Łódź University of Technology, Łódź, POLAND,
email: kjuszczyk@compactprojekt.pl

[3] Professor, Head of Chair of Structural Reliability, Department of Structural Mechanics, Faculty of Civil Engineering, Architecture and Environmental Engineering, Łódź University of Technology, Łódź, POLAND,
email: marcin.kaminski@p.lodz.pl

ABSTRACT: The paper presents basic guidelines for designing reinforcements for steel telecommunication tower structures. Aspects to consider when designing and executing such reinforcements are listed. Proper identification of members with inadequate load-carrying capacity, various shortcomings with regard to structural load-carrying capacity, and technological and economic aspects of reinforcement engineering are emphasized. Assumptions made by reinforcement designers are addressed, with particular attention given to compression members and designing structural reinforcements due to insufficient stability (buckling resistance) of members. The paper provides and discusses examples of tower structure reinforcements that have been already assembled but are incompatible with rules of economic design; the designs are classified into three categories: based on a modification of the static scheme of a structure; consisting in enlarging the cross-section of compression members; and those supposed to increase the global stiffness of a structure.

Keywords: telecommunication towers, steel structures reinforcement, buckling capacity, structure stability, effective design.

1. INTRODUCTION

One area of engineering in which scientific and technological advances as well as continuous development of new technologies can be seen every day is telecommunications. Since the beginning of economic transformation in Poland in 1990s, the telecommunications market has changed considerably: the monopoly practice was abandoned and service providers were allowed to compete with each other. As telecommunication and IT services have become widely affordable, the demand is constantly on the rise. As a natural consequence, the telecommunications infrastructure has to be extended and upgraded. New equipment and ancillaries required to operate the telecommunications network and to provide smooth and failure-free access to services have been continually added to existing base transceiver stations.

Structures supporting telecommunications equipment will be able to meet the growing requirements and safely transfer often a few times larger loads, provided that their load-carrying capacity is improved (Refs 1–4). One of the more effective ways of improving the capacity and service life of a structure is to reinforce it. A correct design and careful assembly of a reinforcement are key for safe operation of telecommunication towers subject to increased loads.

The paper aims to provide guidance as to what should be considered to make reinforcement designs effective and economic, and to point out some common errors made when engineering reinforcements for tower support structures.

2. IDENTIFICATION OF MEMBERS THAT SHOULD BE REINFORCED

The first and most important step when designing a structure reinforcement is to identify a set of members whose load-carrying capacity will be inadequate when the tower load is increased, i.e. ‘the weakest link’ of a structure. What most often requires reinforcing is legs, being the main support members of a tower (Refs 5–8). Sometimes, however, a structure has to be strengthened due to insufficient load-carrying capacity of bracing members or joints, or because it fails to meet the serviceability limit state (SLS) requirement due to too large displacements or twist of the tower, which is directly linked with technological requirements (constant connection with neighboring base transceiver stations). Each of these cases requires a different approach.

3. REINFORCEMENT ENGINEERING

To develop a reinforcement design is usually much more difficult than to produce a new design. The sequence of activities has to be analyzed in detail, maximum unloading of members during upgrade works has to be evaluated, a means of temporary transfer of loads from the upgraded to other members has to be established, and introducing additional supports or bracings has to be planned (Ref. 9).

There are two hypotheses on calculating structural reinforcements:

(1) assuming that the added (strengthening) members are subject only to forces produced by loads imposed when the reinforcement is complete (calculations concern the elastic range); and

(2) assuming that when the stresses attained in the basic cross-section are relevant to the plastic state, the stresses are distributed and balanced within a member both in the basic and the added cross-sections (calculations concern the plastic range) (Ref. 9).

Reinforcement designers are recommended to satisfy general requirements, such as preserving alignment in lattice nodes and arranging strengthening cross-sections such that centers of gravity of the basic and strengthening cross-sections are aligned with each other, and if it is not possible, verifying members at the node considering additional stresses produced by moments occurring due to an eccentric mounting of the additional cross-sections (Ref. 9).

The designers should always bear in mind that, in addition to an effective increase in load-carrying capacity of a structure, the reinforcement design should also meet a number of other conditions, taking into account the following aspects:

- Execution: the reinforcement should be relatively easy to implement; it must not collide with members of an existing structure; little work should be required to mount it; where possible, cutting, drilling or welding members on-site, particularly at height, should be avoided; welds which connect strengthening cross-sections with reinforced members and nodes should be located in places where they can be comfortably made and are accessible for quality control; and locations of new bolts and anchorages should allow easy tightening of nuts.
- Economy: the economic aspects are directly related to execution conditions. Additional members should be of the least weight possible and easy to mount (the higher the price is, the more work is required, the more difficult the execution is, and additional specialized equipment is needed).
- Stability and durability: the reinforcement should be permanently fixed to an existing structure so that transfer of internal forces to additional members is guaranteed and the reinforcement works together with the original structure.

3. REINFORCING COMPRESSION MEMBERS

Depending on the structure operation, technology, and execution conditions, one of the following ways of strengthening members that are mainly compressed is used:

(1) decreasing buckling length of members, which results in additional stiffening of the structure (for slender members in which case the load-carrying capacity is determined by the condition of stability of members);

(2) addition of strengthening members which increase the design cross-sectional area and at the same time do not considerably change slenderness of a bar;

(3) simultaneously increasing the stiffness of the structure (reducing both buckling length and slenderness of a member) and its cross-section (Ref. 9).

For tower structures, reinforcing that involves changing the static scheme by adding intermediate supports and thereby shortening buckling lengths of members, provides good economic results and is most often the best option.

3.1. Reinforcing due to insufficient buckling resistance

Owing to characteristics of members comprising steel lattice structures supporting telecommunications equipment, such as their considerable slenderness and predominant internal forces produced by prevailing wind actions, i.e. axial forces, in a vast majority of cases the load-carrying capacity of a tower is determined by the condition of stability. In flat and space bar structures, the loss of stability can occur as buckling of certain bars or their structure caused by a compressive force or as a local loss of stability, i.e. deformation of the cross-section of compression or bending members. (Ref. 9).

The condition of buckling resistance of a member is characterized by the following relation (Ref. 10):

$$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}}, \tag{1}$$

where:

A – cross-sectional area of the member,

f_y – yield strength of steel of which the member is made,

γ_{M1} – partial factor equal to γ_{M1}=1.0,

χ – buckling factor, given by the formula:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}, \text{ and } \chi \le 1.0, \tag{2}$$

and:

$$\Phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right], \tag{3}$$

where:

$\bar{\lambda}$ - relative slenderness,

α – imperfection factor, depending on the type of cross-section of the member.

The relative slenderness depends directly on the buckling length of the member L_{cr} according to the following formula:

$$\bar{\lambda} = \frac{L_{cr}}{i \cdot \pi \sqrt{\frac{E}{f_y}}}, \tag{4}$$

where:

i – radius of gyration of the cross-section about the relevant axis,

E – Young's modulus.

Given that we deal with already existing structures, we have no control over their material characteristics, which are therefore constant. When analyzing the above formulas it can be easily seen that to increase buckling resistance of members, one should appropriately modify their cross-section parameters or their buckling lengths.

4. EXAMPLES OF REINFORCEMENTS IN TOWER STRUCTURES THAT FAIL TO MEET THE REQUIREMENTS OF EFFECTIVE AND ECONOMIC DESIGN

A number of most commonly encountered deficiencies and shortcomings in tower structural reinforcements are provided below. The examples shown fail to meet at least one of the above mentioned conditions of a correct and optimum design.

4.1. Reinforcements involving a modification of the static scheme of a structure

One typology of telecommunication towers that can be found in Poland most often is a series of structures of a cross-section in the shape of an equilateral triangle and an X-bracing system (except for the top segment having a single bracing system). Legs in these types of towers are made of solid bars, while bracing members of hot-rolled L-sections of various sizes. More details on these structures can be found in Ref.8. Fig. 1 shows a reinforcement of legs in this type of tower made because the buckling resistance requirement was no longer met. Additional horizontal bracing members made of hot-rolled L-sections were used, joined by means of clamps with the legs and by means of gusset plates at the crossing of bracing members, which is meant to decrease the buckling length of main load-carrying members of the tower (Fig. 2). It should be noted, however, that the additional sections are connected both with a leg and at the crossing of bracing L-sections using one bolt, so they should be considered as double-joint members. Such a solution enables the strengthening members to rotate in the nods, which is why they may provide insufficient support for the leg. To make sure that the reinforcement will work correctly, the additional sections should be connected with two bolts, at least on one side, so as to prevent rotation and stiffen the structure.

Fig. 1 Leg reinforcement – an additional horizontal bracing member fixed with one bolt

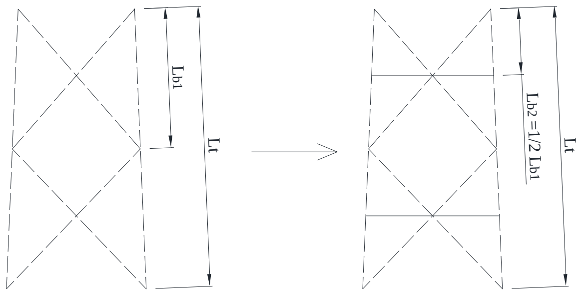

Fig. 2 Changing the static scheme of a structure – shortening the buckling length of legs with an X-bracing system

A similar solution is shown in Fig. 3. Again additional horizontal members were used here to shorten the buckling length of legs, but in this case the joints were designed with two bolts to ensure adequate stiffness of the members. What might raise doubts is the way the additional cross-bars are joined with the existing bracing members of the segment: the members are connected not at the node but slightly below it, and they are not permanently fixed with each other but only held together by a movable piece of sheet plate. This solution imposes adverse bending on the existing diagonal braces, so it fails to provide safe connection of the members.

Fig. 3 Leg reinforcement – an additional horizontal bracing member joined below the node with a movable piece of sheet plate

Another reinforcement of the same type of structure is shown in Fig. 4. In this case additional cross-bars were not fastened at all at the crossing of existing diagonal braces. The cross-bars do not work with the existing bracing members of the tower and are too slender to provide legs with adequate support and to consider their connection point as an additional support.

Fig. 4 Leg reinforcement – an additional horizontal bracing member with no connection at the node

Many solutions which involve shortening the buckling length of a leg in this type of tower can be found in Poland, including designs that are inefficient in terms of economy and difficult to implement. Fig. 5 shows a reinforcement accomplished by adding another X-bracing system shifted by half a segment length (Fig. 6). The additional members are made of framework, which improves their stiffness but requires more work and makes installation on the structure much more difficult to perform. This reinforcement design is also heavy, which undoubtedly makes the construction more expensive. It can be also observed that the additional support introduced by the reinforcement is not always located at the half of the original buckling length of each leg, which again adversely affects the performance of the structure.
Another example of reinforcement that is labor-intensive and difficult to accomplish is shown in Fig. 7. The structure subject to strengthening is a tower with a single bracing system across all the segments. The cross-section of the structure is an equilateral triangle and its legs and diagonal braces are made of circular hollow sections (CHS) of various diameters and wall thicknesses.

Fig. 5 Leg reinforcement – an additional X-bracing pattern made of framework members

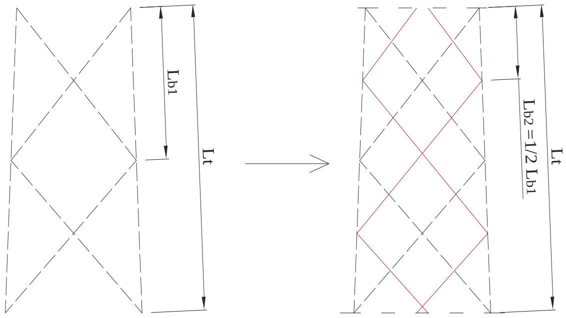

Fig. 6 Leg reinforcement – an additional X-bracing pattern made of framework members

To shorten the buckling length of the tower legs, an additional bracing pattern mirroring the existing one was designed (Fig. 8). This solution is difficult to accomplish in terms of technology (since complex clamps to join the existing and new diagonal braces at the crossing have to be engineered and the nodes of the designed bracing pattern are not symmetrically located to ensure that they do not collide with existing joints) and expensive (since its weight, including additional clamps, is greater than that of the existing bracing system). What is more, this type of joint between diagonal bracing produces additional bending moments in the original bracing system.

Another type of reinforcement for structures described above is shown in Fig. 9. The change in the static scheme is displayed in Fig. 10. The problem in this case seems to be the cross-section of additional strengthening members: they are too slender, which is why they provide no sufficient support for the legs. As far as towers with a single bracing pattern are concerned, one should first find out which members will provide inadequate load-carrying capacity when more load is imposed. In the case shown in Fig. 9 it is likely that the diagonal braces will be the first to buckle and that these members will to the greatest extent affect the load-carrying capacity of the structure; consequently, the reinforcement used will prove inefficient.

Fig. 7 Leg reinforcement in a tower with a single bracing pattern – additional diagonal braces mirroring the original bracing pattern

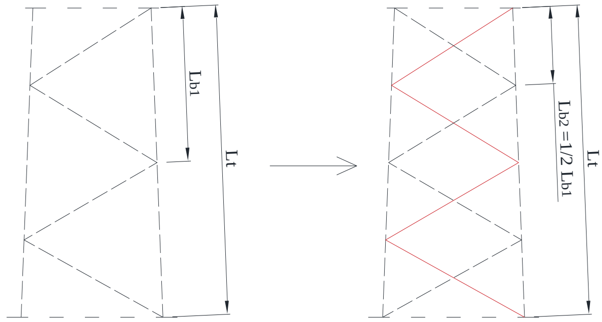

Fig. 8 Reinforcement scheme of a tower with a single bracing pattern – additional diagonal braces mirroring the original bracing pattern

Fig. 9 Leg reinforcement in a tower with a single bracing pattern – additional cross-bars

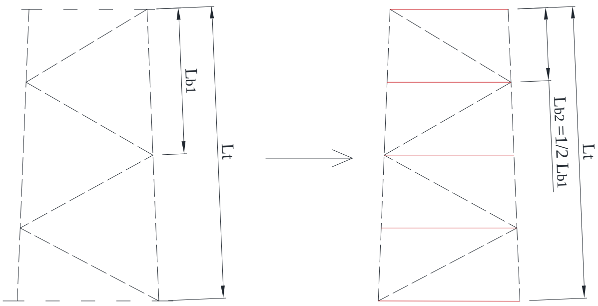

Fig. 10 Reinforcement scheme of a tower with a single bracing pattern – additional cross-bars

The last example of strengthening a tower structure involving a modification of its static scheme is a solution meant to increase the load-carrying capacity of the tower’s diagonal braces (Fig. 11). The additional members that can be seen in the photo were supposed to shorten the buckling length of the L-sections used in the bracing pattern. We can see in the photo that these members support the diagonal braces only in one direction, namely in the plane of the tower wall. They fail to prevent buckling of the diagonal braces out of the plane of the wall. To make the reinforcement fully effective, one should provide additional members to stiffen the diagonal braces also in the other direction.

Fig. 11 Reinforcement of diagonal braces – shortening the buckling length in the plane of the tower wall

4.2. Reinforcements involving an increase in the cross-section of compression members

Instead of modifying the static scheme of a structure, one can enlarge the cross-section of those members whose load-carrying capacity is insufficient. Such an operation usually results in greater stiffness of a member since it becomes less slender. Figure 12 displays an example of reinforcing a tower with a cross-section in the shape of an equilateral triangle, legs made of solid bars, and diagonal braces made of hot-rolled L-sections. Hot-rolled C-sections were attached to the leg bars, which increased the cross-section of the legs. The reinforcement may seem very massive. Clamps are spaced not far apart to satisfy the requirement of correct integration of the strengthening and strengthened members. Drawbacks of this solution include high weight of the additional structure and its eccentric mounting which introduces adverse eccentricity. In this case it is difficult to establish a correct integration of the members, how internal forces are transferred to the new members, and how large these forces are.

A similar method was used in the case of a tower with a triangle cross-section and legs and diagonal braces made of L-sections (Fig. 13). The strengthening members are again made of hot-rolled C-sections and welded to tower legs using spacers with appropriate spacing.

It seems difficult to establish by means of calculations what part of the force will be taken by the strengthening members, and due to its weight the reinforcement seems rather uneconomic. Figure 14 shows an example of an attempt to reinforce the same type of tower by increasing the cross-section of its legs by means of additional members made of flat bars. The photos indicate that the strengthening members are not appropriately integrated with existing L-sections and therefore they do not participate in the work of the structure but only impose an additional load, since their weight is close to that of the existing L-sections. In the lower photo a buckling of one of the tower legs can be seen, which proves that the additional members fail to strengthen the existing structure.

Another example of inefficient tower reinforcement is provided in Fig. 15. Additional C-sections and flat bars were attached to existing diagonal braces made of cold-rolled C-sections and CHSs to increase the cross-section of the members. The extra C-sections were mounted with bolts fitted though holes in flanges, and the flat bars were fixed to CHSs using clamps. The reinforced tower has a square cross-section, legs made of CHSs, and diagonal braces made of cold-rolled C-sections, circular and square hollow sections, or solid bars, depending on the segment. Bottom segments feature an X-bracing pattern, while a single bracing pattern is used in the three upper segments. The reinforcement is ineffective because this way of enlarging the cross-section only slightly improves the stiffness and buckling resistance of members that are prone to lose stability, but at the same time results in a considerably greater weight of the members and, particularly in the case of strengthening members made of flat bars, larger upwind surface area, and thus greater load. It also should be noted that the flat bars used do not reach the nodes and their connection with existing members enables them to rotate about axes of the hollow sections; this way of integration of cross-sections could not be considered as a correctly assembled combined cross-section. It is difficult to determine whether and how internal forces will be transferred to the additional members, allowing them to work as a whole with the existing structure.

Fig. 12 Leg reinforcement – additional C-sections mounted by means of clamps

Fig. 13 Leg reinforcement – additional C-sections mounted by means of spacers

4.3. Reinforcements supposed to increase the global stiffness of a structure

Apart from providing sufficient structural load-carrying capacity, a key issue in the case of telecommunication towers is also to satisfy criteria concerning the serviceability limit state (SLS), namely to ensure that maximum displacements and twists of tower tops are not exceeded, which enables reliable operation of BTSs installed on them.

An example of reinforcement used for a tower of a square cross-section in order to reduce the displacements is shown in Fig. 16.

Fig. 14 Leg reinforcement – additional members in the form of flat bars, not integrated with the existing structure

Fig. 15 Increasing the cross-section of diagonal braces by attaching additional flat bars and C-sections to existing members

Horizontal diaphragms made of L-sections and solid bars, compressed by means of bottle screws, were used here. Owing to the shape of the tower cross-section (a square is a geometrically variable figure), the tower is vulnerable to deformations caused by a twist of the core. This structure is also considerably slender, which makes its top prone to large displacements under horizontal load. Although the diaphragms have beneficial role in limiting the twist of the tower core, they have no impact on its displacement in load conditions. To reduce the tower top displacements, the global stiffness of the tower should be increased, i.e. its slenderness should be reduced (which requires redesigning the geometry of the structure, mainly by providing a greater distance between the legs and greater cross-sections of members) or additional supports should be introduced, e.g. in the form of guys supposed to stabilize the structure.

5. CONCLUSIONS

The examples of reinforcements implemented in tower structures discussed above are not entirely wrong. Most of them is likely to improve load-carrying capacity, stiffness or stability of structures to some extent. They were designed, however, based on some assumptions on the work of the structure, load transfer, and work of strengthening and strengthened members as a whole; these assumptions are not valid when some key aspects are neglected (such as correct integration of reinforcing members with an existing structure). Given the above, it is difficult to predict whether, how and to what extent the reinforcements presented in the paper will improve capacities of existing structures.

Some of these reinforcements fail to comply with the rules of economic and efficient engineering, although it is highly probable that they actually act as reinforcements. This pertains to those cases in which the additional strengthening structure has incomparably greater weight or involves fabrication and assembly costs that greatly exceed benefits related to the improved load-carrying capacity obtained by implementing such a structure.

Fig. 16 Stiffening a tower structure in the form of horizontal diaphragms to prevent its twist

By analyzing the examples provided above as well as guidelines for designing effective reinforcements, the following conclusions can be drawn:

- Designers of reinforcements for telecommunication towers should first identify the actual ‘weakest link’ of a structure, namely a member or a set of members that actually should be strengthened.
- The reinforcement should be designed to address insufficient capacities, such as stability and load-carrying capacity of a cross-section or joints or to help satisfy serviceability conditions.
- Particular attention should be paid to correct integration of strengthening members with an existing structure so that they would work with each other as a whole.
- When selecting a means and form of reinforcement, one should check whether the additional load imposed by the reinforcement (weight of new members, upwind surface area, and the shape of new members resulting in higher horizontal load) does not match or even exceed the surplus load-carrying capacity that it is supposed to deliver.
- Apart from improving the structural load-carrying capacity following the implementation of appropriate reinforcement, there are other issues to consider, such as whether the solution is cost-effective and easy to engineer and assemble.

REFERENCES

1. Mills JE, Ma X, Zhuge Y.: Experimental study on multi-panel retrofitted steel transmission towers. Journal of Constructional Steel Reaserch, 78, 2012, pp.: 58-67.
2. Zhuge Y, Mills JE, Ma X.: Modelling of steel lattice tower angle legs reinforced for increased capacity. Engineering Structures, 43, 2012, pp.: 160-168.
3. Stamatopoulos GN.: Assessment of Strength and Measures to

Upgrade a Telecommunication Steel Tower. International Journal of Steel Structures, 13(2), 2013, pp.: 331-340.

4. Albermani F, Mahendran M, Kitipornchai S.: Upgrading of transmission towers using a diaphragm bracing system. Engineering Structures, 26, 2004, pp.: 735-744.
5. Szafran J.: An experimental investigation into failure mechanism of a full-scale 40 m high steel telecommunication tower. Engineering Failure Mechanism, 54, 2015, pp.: 131-145.
6. Kamiński M., Szafran J.: From full-scale testing of steel lattice towers to stochastic reliability analysis. Archives of Mechanics, 69(4-5), 2017, pp.: 371-388.
7. Szafran J., Rykaluk K.: A full-scale experiment of a lattice telecommunication tower under breaking load. Journal of Constructional Steel Research, 120, 2016, pp.: 160-175.
8. Szafran J., Juszczyk K., Kamiński M.: Full-scale testing of steel lattice towers: requirements, preparation, execution, challenges, and the results. Lightweight Structures in Civil Engineering - Contemporary Problems. Rzeszów University of Technology, 2015.
9. Małowski E., Spiżewska D.: Wzmacnianie konstrukcji budowlanych. Arkady, Warszawa 2002.
10. PN-EN 1993-1-1: Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings. European Commitee for Standardization, 2015.