European Commission
Research Programme of the Research Fund for Coal and Steel

ANGELHY

Innovative solutions for design and strengthening of telecommunications and transmission lattice towers using large angles from high strength steel and hybrid techniques of angles with FRP strips

WORK PACKAGE 6 – DELIVERABLE 6.1

COMPREHENSIVE OVERVIEW

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Grant Agreement Number: 753993

15/12/2017

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TABLE OF CONTENTS

1 Introduction

Steel lattice towers are composed of small member sizes and have the advantages of easy transport and on-site erection, without the need of special vehicles or heavy crane machinery. Such towers are built for telecommunication purposes or for electrical transmission in mountainous terrain of very limited accessibility where easy transport and erection are the main criteria for the structural scheme selection. It is therefore expected that such types of towers will continue to be built in the future in most regions of Europe, especially in those where plan space exists, the terrain is mountainous, the population is not very dense and the accessibility by vehicles or heavy machinery is limited. The most common cross-sectional shape for the tower members are the equal leg angles due to their beneficial connectivity. The leg length ranges from small dimensions up to 300 mm for heavy duty transmission towers. High strength steel is increasingly used as it leads to smaller section sizes that attract less wind loading. Finally, single or built-up angle sections are used as truss members in other structural applications as well.

Strengthening of towers, especially for telecommunication purposes, is often needed due to increase of the tower occupation and therefore of loads. Existing technologies and code provisions lead to a specific strengthening method that is often proven to be uneconomic. The application of hybrid technologies or alternative strengthening methods, as anticipated in this project would therefore be of high advantage and increase the competitiveness of steel towers.

In addition, existing European Codes are observed to not fully cover angle member design, especially from high strength steel. Moreover, existing provisions on the spacing of battens for back-to-back angles and star battened angle members were proven to be too severe or too complicated.

Herein, the state-of-the-art on lattice towers will be presented, along with the objectives of the ANGELHY programme.

2 European and worldwide state-of-the-art and current practice

2.1 General

Lattice towers are extensively built in Europe and worldwide to serve telecommunication or power transmission purposes. This is due to the fact that such towers are very often installed in mountainous terrain with very limited access to heavy vehicles. Accordingly, a lattice tower structural system, which may be transported and erected by light machinery and equipment, is almost the only possible solution. On the other hand, lattice towers need more ground space compared to cylindrical, octagonal or similar shell-type systems. However, ground space is plentifully available in remote places outside the densely populated regions, a fact that is valid in most, apart a few, countries or regions of Europe. In conclusion, it may be argued that besides general structural engineering purposes, lattice towers are and will remain for a long time the main structural system for telecommunication and power transmission.

The members of such towers are frequently composed of equal leg angle sections that are often preferred to tubular sections due to their easier connection that results in a simpler erection, a requirement set by most telecommunication or power providers. Angles sizes range from light to heavy sections with leg lengths up to 300 mm that are lately produced in Europe and are employed for towers with increased height. Appropriate long life corrosion protection is ensured with the application of angles, since all angle sizes are fully amenable to hot dip galvanizing in contrast to several other types of open or closed sections. The use of high strength steel is important as it results in smaller member cross sections that in turn attract less wind loading, which is the most important variable action on lattice towers, and lead to further structural weight reduction. Finally, lattice members from single angles or built-up sections of two individual angles connected by batten plates are also extensively used for buildings and other civil engineering applications, as well as for strengthening existing lattice towers.

The European specification for the structural design of lattice towers is EN 1993-3-1 [2] as part of the Eurocode family. For overhead electrical lines there exists a CENELEC Code, EN 50341 [5], which covers in a normative Annex the design of lattice transmission towers. Although EN 50341 mentions the general Eurocode part, EN 1993-1-1 [1], it differs in many aspects from [2] as e.g. in the values of the partial safety factors for buckling γ_{M1} or the type of buckling curves for angles. EN 50341 allows design by full scale testing, in which case a higher buckling curve, in fact curve “a”, may be chosen. However, it draws design conclusions from a single test comparing the ultimate load achieved in the test with the corresponding one from calculations, neglecting the fact that the results of an individual test are influenced by potential material overstrength, strain hardening or other parameters the values of which are associated with statistical uncertainties. Consequently, it does not touch reliability issues as done in the structural Eurocodes as described in EN 1990 [4].

Angles have been used from the very beginning of steel construction due to their potential for easy transport and easy on-site erection. Angle sections have special features in that: a) they have only one axis of symmetry, b) their principal axes do not coincide with the geometric axes and c) they have very small rigidity to uniform and non-uniform torsion [7]. Consequently, design expressions for other common shapes, as e.g. those included in EN 1993-1-1, may not be used for angle sections. It should be pointed out that, despite their wide application, angles have received very limited to no European research funding compared to other types of open or closed sections. It is therefore not surprising that Eurocode 3 covers member design with angle cross sections mainly for the case of axial compression or tension, saying little to nothing specifically for angle members subjected to axial force, bending and torsion.

In contrast, recognising the fact that angles should be treated differently than other sections, specific design specifications for single angle members were issued in the US [6] as well as in Australia [11, 12, 13], with due consideration of inelastic bending capacities. Design expressions for the buckling resistance of cold-formed angle sections prone to local buckling were derived in [12], while in [13] direct strength equations were proposed for class 4 angles subjected to combined bending and compression. The effects of wind and seismic actions on telecommunication towers are reported by the partners of this projects in [14, 15], while [26] reports on results of a related research project of limited scope. On the other hand, research and corresponding rules for angles with high strength steel are still rather scarce. The overall behaviour in the context of the complete structure may be determined by full scale tests. Indeed, such tests have been common industry practice since the beginning for latticed transmission towers. A collection and critical review of such tests as well as practical advice for conducting future tests are reported in [27].

The possibility to strengthen the members of lattice towers by introducing carbon fibre reinforced polymers (CFRP) strips will be investigated in this project. The application of CFRP-strips in enlarging the bending capacity of steel I- or HEA-profiles was studied in [31], [32], or [33]. Strengthening to increase the compression capacity of steel hollow sections was studied in [34], [35]. For angle profiles, FRP-strips were used for rehabilitation purposes due to corrosion [36], or for enlarging the axial capacity [37]. Strengthening of angle section columns with FRPs was studied by a limited number of experiments at the Institute of Steel Structures, NTUA, as part of a diploma thesis [30].

Despite the aforementioned works and in contrast to concrete structures, little research effort was made internationally to strengthening of steel profiles with FRPs up to the present. It is therefore not surprising that, in contrast to reinforced concrete, practical applications for FRP-interventions in steel profiles are rather scarce and there exist no Codes or Recommendations at present at European level apart from a design guide [38].

2.2 Special issues of telecommunication lattice towers

Angles have been used in construction almost as long as structural steel has been around and were commonly used as components of built-up shapes. For example, I-sections and channels were made in the past by attaching angles to plates. More recently, angles have been used as braces, tension members, struts and lintels. Double angles also have been used as chords or diagonals in trusses. Angles give the possibility of easy transport and easy on-site connection. They are not susceptible to the well-known problems, such as the appearance of cracks after hot dip galvanizing, unlike other types of open or closed cross sections. Equal angle sections are widely used today as legs or bracing members in free standing lattice towers that are erected on sites with difficult accessibility, predominantly in two sectors: towers and guyed masts for telecommunication purposes, or transmission towers (Fig. 2.1).

Figure 2.1: Lattice towers: telecommunication towers and transmission towers.

Main leg members run continuously over the height of the tower and are appropriately spliced at certain distances; bracing members are provided in various bracing patterns. Secondary bracings may be used to subdivide the primary bracing of main leg members. Member cross sections may vary from small to large angles, depending on the height and type of the tower and the loading conditions. Very heavy angles, with leg length up to 300 mm, possibly of high strength steel S 420 or 460 (except the largest sections L300 which are not yet available in S 460), are used for heavy duty transmission towers. Members are connected by one or more bolts on one leg either directly or through gusset plates. This results in eccentricities leading to bending moments and, if more bolts are used, to the development of partial end restraints that modify the buckling length. Wind on the structure and the conductors (power lines) is the main loading for such towers.

Severe weather conditions combining low temperatures, snow and wind are often the governing loading condition. Wet snow accumulates in the form of ice on towers and conductors (Fig. 2.2), adding to gravity loads, dramatically increasing wind drag and leading to tower collapse (Fig. 2.3). This is the leading cause for tower collapses in operation [26] and has frequently led to widespread blackouts that are difficult to recover from simply due to network design. Transmission towers of different structural functions are combined for each stretch of a power grid (Table 2.1): Tangent towers mainly carry the gravity load of conductors, needing dead-end and/or angle towers at regular points to offer lateral resistance to the group [27] (Fig. 2.4). Thus, a single tower rarely fails without taking out a number of adjacent ones. Together with, possibly, optimistic Code provisions and lower safety factors, this makes transmission towers most susceptible to extreme weather and may lead to cascading failures with implications far beyond their own integrity.

(a) (b) (c)

Figure 2.2: Icing of (a) transmission tower; (b) conductor; (c) telecommunication tower.

Figure 2.3: Collapse of a transmission tower.

Types of Towers

Type A Tower (Tangent Tower with suspension string)	• Used on straight runs and up to 2° line diversion
Type B Tower (Small Angle Tower with tension string)	• Used for line deviation from 2° to 15°
Type C Tower (Medium Angle Tower with tension string).	• Used for line deviation from 15° to 30°.
Type D Tower (Large angle tower with tension string)	• Used for line deviation from 30° to 60°
Type E Tower (Dead End Tower with tension string)	• Used for line termination & starting
Suspension Tower (Span ≈ 1000 m)	• Used for River crossing, Mountain crossing etc.
Transposition Tower	• Used for transposition of tower

Table 2.1: Types of power transmission towers.

Telecommunication towers constitute a special case due to the fact that dead load and, especially, wind loading frequently varies during their design life due to modifications, like the provision of more and larger antennas which may result in a requirement for strengthening the structure. For bracing members, the old section may be replaced by a larger angle. This is not feasible for leg members, thus, a second angle is usually inserted and connected with the existing section to form a built-up member. For ease of erection, a star battened configuration may be used, where the two angles are connected by pairs of battens in two perpendicular planes (Fig. 2.5). Subdividing the bracing patterns, to reduce the slenderness, is another option where the original slenderness is very high. In absence of code-supported design recommendations, the cross section of the new leg is usually identical to the cross section of the existing leg, although a smaller section could be sufficient from purely static considerations. Strengthening existing tower angle members using smaller angles than the existing ones may lead to substantial economic benefits which may be summarized as follows: a) Less weight, b) less area and accordingly less additional wind loading, c) less erection effort. In addition, it is expected that such types of built-up members with unequal angles will be used in other applications too, once appropriate design rules are developed. However, an exact quantification of the benefits in terms of monetary gains can only be provided on a case-by-case basis.

(a) (b) (c)

Figure 2.4: . Different types of transmission towers: (a) Tangent double-circuit tower, insulators are hanging vertically, little capacity of resisting unbalanced horizontal loads; (b) Dead end double-circuit tower, capable of anchoring a sequence of suspension towers, having two separate sets of insulators and two bundles of conductors in the forward and the backward direction for each line (connected by a characteristic slack length of conducting cable; (c) Tangent waist-type tower, insulators arranged vertically in a V formation.

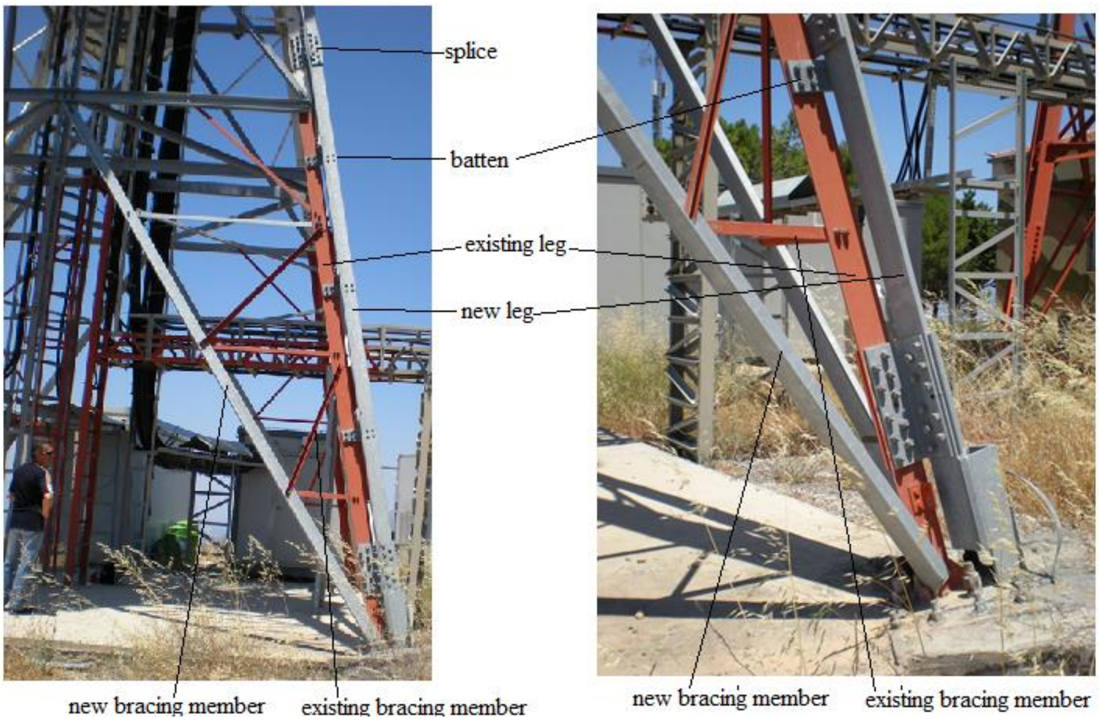

Figure 2.5: Strengthening of existing lattice tower.

2.3 Strengthening of steel members with composite materials

A promising alternative for strengthening existing towers with the benefits described before is by using hybrid technologies. In these technologies angle sections are strengthened by means of Fibre Reinforced Polymers (FRPs). The hybrid solution is expected to be most advantageous from the structural and constructional point of view due to the combination of the following: a) no increase of the reference wind area and therefore of the wind forces, b) no increase of structural self-weight, c) no need for exchange of brace profiles, d) adjustment and fine tuning of the extent of strengthening to the design needs. Preparatory tests as reported in [30] have been performed recently in the Institute of Steel Structures, NTUA. Here angle sections were strengthened by carbon FRP (CFRP) wraps, applied on the two external faces. The experimental investigations comprised two three-point bending and two column tests. The experimental set-up, the specimen geometry and the loading conditions are indicated in Figure 2.6. The tests provided first data for the application of such a technique and showed the enhancement in strength and especially ductility of the hybrid members as compared to the purely steel ones. However, in the current project CFRP strips instead of wraps will be used, which are expected to further increase the strength.

Structures in Europe are designed in accordance with the relevant Eurocodes. Lattice towers are covered by the provisions of CEN EN 1993-3-1 that is part of the Eurocode family. However, structural design for transmission towers is embedded in CENELEC EN 50341 that refers to overhead electrical lines and deals additionally with many non-structural issues. EN 50341 is under review and currently in draft 4. The draft makes reference to EN 1993-1-1 for angle design, but not to EN1993-3-1. EN 50341 foresees design assisted by full scale testing of the tower, but does not address issues of reliability and test evaluation on a statistical basis as required in the family of Eurocodes by the detailed provisions of EN 1990.

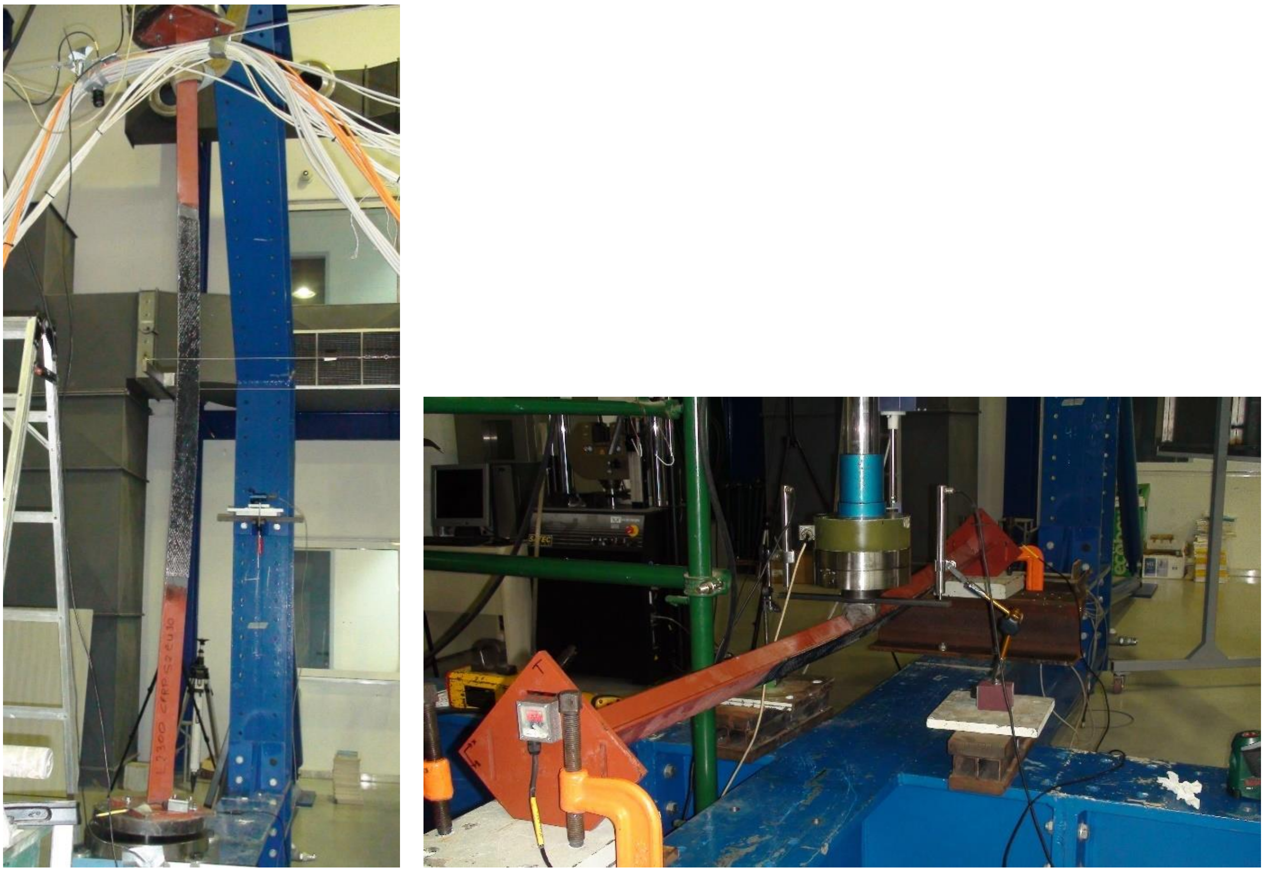

Figure 2.6: Test set-up for compression and bending tests recently performed in NTUA [30].

2.4 Limitations of current design rules for angle members

In spite of their long history of usage, the design of members composed of angles, and particularly single angles, has not become as familiar to the engineering profession as the design of other, more common shapes. The information included in the Eurocodes [1, 2] for angle member design is rather limited. To fill this gap experimental, numerical and analytical investigations have been carried out recently in NTUA as reported by Vayas et al in [26] and [8]. Experimental investigations referred to eight (8) three point bending and thirty-one (31) compression tests on steel angles. The set-up for these tests was similar to Figure 2.6. Compression was applied with some eccentricity to account for the effect of combined loading. Accompanying numerical non-linear analyses indicated the angle potential to stable inelastic deformations (Fig. 2.7).

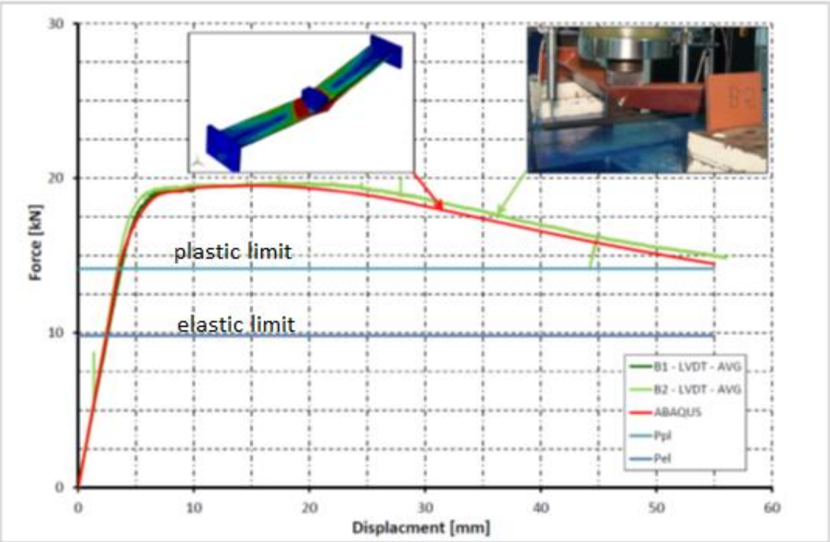

Figure 2.7: Experimental and numerical investigations on angles [26].

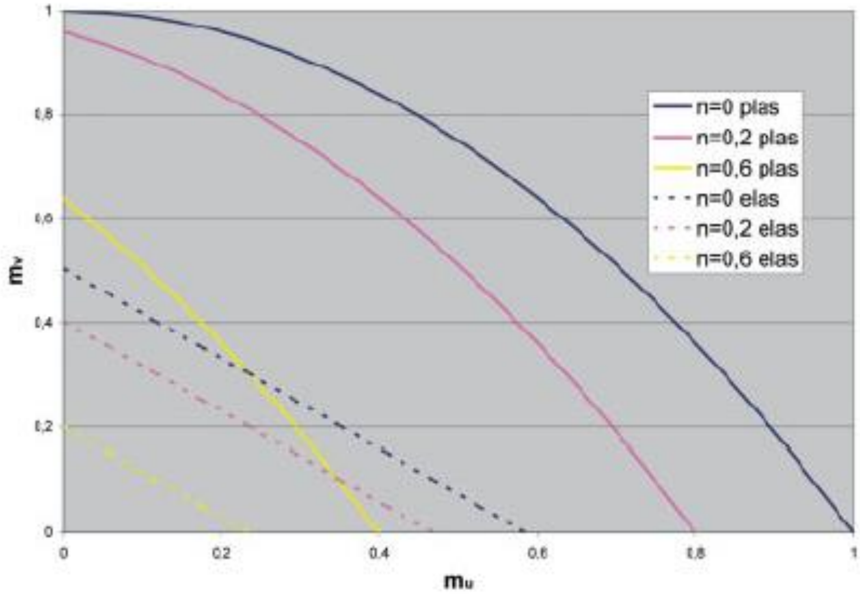

Figure 2.8: Elastic and plastic interaction relations for angles [8].

Analytic investigations showed the large inelastic capacities of angles in cross section level to combined loading (Fig. 2.8). However, EN 1993-1-1 does not include appropriate interaction relations as it does for other types of open and closed cross sections (I-, H- sections, RHS, CHS).
Another issue refers to appropriate modelling of lattice towers. Such towers are sometimes analysed in practice as trusses, where members carry only axial forces. Although this might reflect the conditions at failure, there are several reasons that such models do not adequately reflect the actual tower behaviour at least for the serviceability and fatigue limit states: a) Loads and especially wind loads are directly imposed on the entire member length and not only at joints introducing bending moments in members. b) Tower legs run continuously and are not pin-connected at their ends. c) Truss models induce more flexibility in the system and might lead to erratic modal vibration frequencies and dynamic wind effects. Improved tower models use beam elements for members, possibly introducing hinges at bracing member ends. These models result in axial forces as well as

bending moments in members due to both local and overall loading. It is therefore inconsistent, and possibly not safe, to perform member design neglecting moments as is usually done in practice.
Neglect of the existing moments in design might be balanced by neglecting inelastic capacities. However, during full scale testing these capacities are fully effective, possibly leading to unsafe design if the design criteria are based solely on full scale testing as foreseen in [5]. At this point, it should be stated that experience in Europe indicates that telecommunication towers did not suffer from collapses due to wind while transmission towers, where full scale testing is possible, did collapse in large numbers during extreme weather conditions resulting in high social costs.

For a built-up member made of two angles, it was the usual practice to consider the member as a single integral member provided that the spacing between interconnections does not exceed 40 or 50 times the minimum radius of gyration (i_{min}) [18] while the limit is $15 \cdot i_{min}$ in EN 1993-1-1 [1]. Based on the principles of EC3, a simplified method has been proposed in [19] but it remains too conservative in comparison with former practice. So, the limit of $15 \cdot i_{min}$ should be revised on the basis of experimental and numerical investigations.

Moreover, current design rules cover built-up members where individual angles are of identical section. However, assessment of existing towers showed that a lighter section could be used for reinforcement leading to built-up members with different sections for which design rules do not exist at all. Accordingly, investigations are necessary to extend the rules mentioned earlier to this type of members.

3 Project objective and proposed methodology

The objective of the ANGELHY project is to study members with single and built-up angle sections focusing on high strength steel and large sections, introduce a new type of built-up members composed of two angle sections of different sizes, appropriate for strengthening of tower members and introduce innovative hybrid solutions from FRP-strengthened angles for purpose of strengthening existing members. The studies will lead to the development of design rules, appropriate for introduction in European Codes, ultimately promoting innovation, safety, economy and sustainability. Constructional innovation refers to the new type of built-up members and the hybrid solutions, while safety and economy to the design rules for heavy sections, high strength steel and closely spaced built-up members, as well as to a robust reliability-consistent design on a performance-basis of single and groups of towers [20-23]. Six interdependent actions are envisaged for a successful completion, each one targeted at bringing significant added value to the corresponding area of interest and ascertain the appropriate management of the project.

3.1 Market analysis - Case studies – Code review

Structural typologies for telecommunication and transmission towers will be identified. On this basis, six case studies of new and existing strengthened towers will be worked out. Market analysis for the future needs of transmission towers, especially concerning large section and high strength steel will be performed. Based on the outcome of the case studies, the provisions of the current European regulations EN 1993-1-1, 1993-3-1 and 50341 will be critically reviewed with due consideration of design assumptions. Special attention will be given to whether the provisions for design assisted by full scale testing comply with the requirements set in EN 1990 with respect to validation, treatment of uncertainties, derivation of partial safety factors and other issues concerning reliability.

3.2 Development of rules for design of steel angle members

Experimental and numerical investigations will be performed to study strength and stability of angles subjected to combined loading conditions. Experimental investigations refer to column buckling tests on large angle sections (leg length ≥ 150 mm) from high strength steel (S460). These will complete the experimental database for high strength steel, while for carbon steel and smaller sections existing experimental results will be used, e.g. those reported by Vayas et al in [26]. Numerical investigations refer to geometric and material nonlinear analyses including imperfections (GMNIA analyses) with models duly calibrated on the tests that will extend the parameter range of experimental tests (Fig. 3.1). On this basis, design rules for steel angle cross sections and members will be developed. For cross sections resistance a smooth rather than a stepped curve for the implications of local buckling will be followed, following the results and recommendations of the SEMI-COMP project.

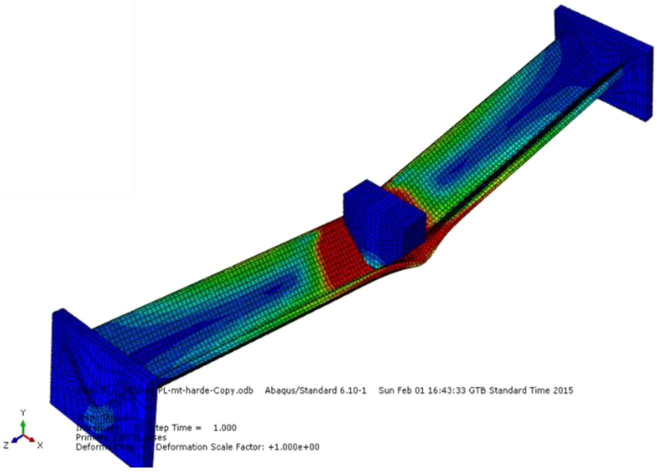

Figure 3.1: Numerical shell element models (here: three-point bending test).

Furthermore, by full scale tests (Fig. 3.2) and corresponding non-linear analyses the member response in the context of the complete structure will be followed up to and beyond the maximal loading. This will allow the identification of possible load shedding between bracing and leg members and the derivation of global failure modes that will assist in the interpretation and assessment of full-scale tests foreseen in the Codes. The influence of important properties, like realistic connection conditions, bracing configuration, or eccentricities will be studied and conclusions will be drawn on buckling lengths, development of secondary bending moments etc.

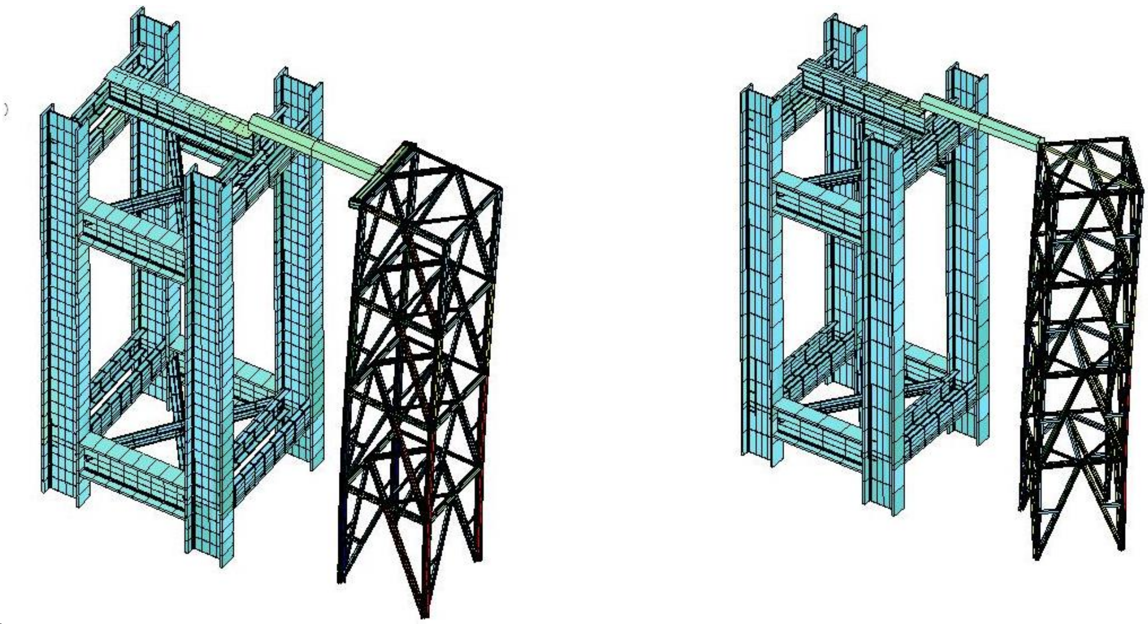

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Figure 3.2: NTUA Loading Frame 1 with specimens O-1 and D-1 (orthogonal and diagonal loading).

3.3 Development of rules for design of hybrid members composed of steel angles and FRP strips

A promising strengthening measure for tower members seems to be the application of CFRP-strips over the entire or partial profile length. The degree of strengthening can be accommodated by selecting the appropriate mechanical properties, thickness and number of layers of the strips. Research on this field is rather scarce (Fig. 3.3) so that the proposed project will certainly fill a large knowledge gap in this respect. Experimental and numerical/analytical investigations will be performed. Experimental investigations refer to bending and buckling tests on hybrid angle members. Failure modes, whether of the individual components or the connecting matrix, will be observed. The parameter range of the experiments will be extended by non-linear analyses, calibrated to the experimental results, using numerical shell models for the hybrid members. Design rules and corresponding partial safety factors will be developed that will allow design of such strengthening measures.

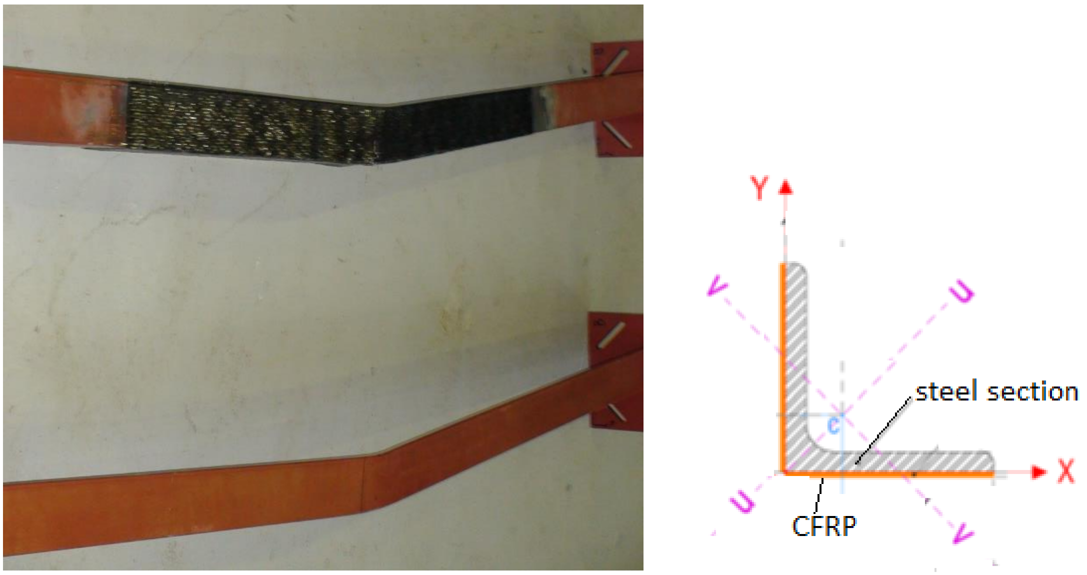

Figure 3.3: Strengthening of angle sections with CFRP [30].

3.4 Development of rules for member design of closely spaced built-up compression members with angle sections and innovative built-up members

The focus is on closely spaced built-up members made of angles that are very common for lattice girders and in strengthening applications for towers. Existing provisions on the spacing of battens for back-to-back angles and star battened angle members are felt to be too severe or too complicated. Experimental investigations for both configurations will be performed. They will serve for calibrating subsequent numerical studies by means of GMNIA analyses. Failure modes will be identified depending on the connection details. The influence of eccentricities will be studied and the earlier provisions for batten spacing will be extended.

Furthermore, experimental and numerical investigations will be carried out on built-up members made of two angles of different sections that may be used within the frame of strengthening measures for existing towers. Appropriate design methods will be developed for this innovative type of built-up members that are not covered in Codes yet.

3.5 Design guide preparation and the validation at the structure and ensemble level

The drafting and validation of the proposed design rules will be undertaken. The practical implementation of the experimental and numerical activity of the project will be summarized in a design guide. The proposed document will include recommendations for analysis and design of lattice towers, design methods for angles and closely spaced built-up members from angles. As case studies, one cellular telecommunication tower and three different types of transmission towers will be employed. They will be designed as existing, new and upgraded existing structures, using the proposed guidelines in the latter two cases, for a grand total of 12 different structural realizations. Their performance will be assessed both as isolated single structures and, for the transmission towers, as a self-supported interconnected sequence of multiple structures stretching over several kilometres. In all cases, a performance-based assessment of the actual system safety will be conducted, fully incorporating all pertinent sources of aleatory and epistemic uncertainty in loads (especially the governing wind, ice and temperature conditions), materials and geometry [21], making extensive use of existing literature to determine the distribution of all random quantities. This will allow the comprehensive evaluation of the reliability infused by the design rules. Pursuant to Eurocode safety standards, all design equations and their inherent safety factors will be, thus, fine-tuned (wherever needed) to ensure full compliance *at the structural level*. In addition, the comprehensive view offered by evaluating a transmission tower ensemble will provide much-needed insight into the effect of section-level code provisions and how this translates at the *system/network level*.

3.6 Codify and disseminate project findings

A number of journal and conference publications are envisioned, together with the distribution of the relevant design guide at targeted mini-symposia, workshops and via national engineering associations. In addition, specific proposals for Code amendments regarding the design of single angle and built-up cross sections and members will be discussed and written down for all relevant clauses of EN1993-1-1, EN1993-3-1 and EN 50341-1.

4 Anticipated results

4.1 Scope

A large number of lattice towers exist and are being built in Europe and elsewhere for telecommunication purposes, or as transmission towers. The members of such towers are frequently composed of angle sections and more specifically of angles with equal legs. For demanding applications, heavy angle sections with leg lengths up to 300 mm and possibly made of high strength steel may be required. Existing European Codes do not appropriately address angle verifications at the level of cross section and member design. They neglect possible inelastic capacities and do not provide information on cross section member design for simultaneous axial forces and moments. Moreover, existing European Codes may contain over-conservative or unsafe prescriptions, without accurate knowledge of where conservative assumptions compensate unsafe ones.

Due to their geometrical properties, angles and built-up members composed of angles may not be designed by the same expressions as other common shapes. Angles: a) are mono-symmetric and not double symmetric sections, b) their principal axes do not coincide with the geometric axes, where frequently direct loading applies, c) as open sections they have low torsional rigidity, d) due to the lack of two flanges they have very limited warping rigidity, e) torsional buckling may be covered by local buckling and f) they have large inelastic capacity if local buckling does not prevail. All these lead to the conclusion that relations for cross section and member design may look very different compared to open doubly symmetric or closed sections. Gusset plates, end connection geometry and bracing configuration may considerably influence buckling lengths. In addition, configurations, distances of batten plates and connection properties may well influence the response of built-up members.

The current project concentrates on the establishment of design rules for steel and hybrid angle sections, as well as built-up members composed of angles that are used in lattice towers and masts, with its objectives being the promotion of:

- ***Innovation***

Innovative products are introduced for use in lattice towers. More specifically, very large angle sections made of high strength steel are currently produced by European companies. Such angles may be used in very demanding applications such as for the next phase of transmission towers now planned in many countries. The derivation of new design rules constitutes a contribution to innovation.

Moreover, the application of hybrid techniques, like standard rolled angle sections strengthened with CFRP materials is a promising area for future research and field applications. If the successful introduction of such materials for strengthening reinforced concrete structures can be extended to structural steel towers, the development of a new profitable market may be possible.

Finally, innovative built-up members composed of two angles of different sizes are studied that may be employed in towers and many other civil engineering applications, primarily for strengthening existing lattices but not excluding new applications.

- ***Economy***

However, existing experimental and numerical investigations suggest that angles may well develop inelastic strength well beyond the elastic one that is exploited by European standards. The capitalization of the inelastic strength of angles sections leads to an optimized design of new lattice tower in terms of weight and costs. Moreover, by application of improved design methods it may be

possible for existing towers to well sustain increasing live loads without need for strengthening thus increasing economy. This reduction will make steel towers more attractive and competitive to reinforced concrete ones.
Secondly, when a posterior strengthening of lattice towers is needed, it is currently realized by a second angle which is connected with the existing section to form a built-up member. This second angle is of equal size, even if not needed, due to the fact that the design of the resulting built-up member is supported by European codes. Here the development of rules for built-up members with two angles of unequal size will contribute to economy.
Economy is more substantially served by the introduction of hybrid technologies. They attract less wild loads and, more importantly, are easier to install due to no need for hole drilling, no need for bolt driving and less additional structural weight.
Finally, the relaxation of existing design rules for closely spaced built-up members made of angles that are felt to be too severe will contribute to economy.

- ***Safety***

Safety is served by the introduction of new experimental and numerical evidence concerning the behaviour of single, built-up and hybrid angle members, as well as subassemblies and complete lattice towers. It is also served by definition of appropriate design values after statistical evaluation of test and numerical results. Requirements will be set for exploitation of experimental results to ensure that design assisted by full scale testing is consistent with existing European standards and more specifically with the requirements of the Eurocodes. In addition, the reliability of single lattice towers and sequences of interconnected transmission towers will be improved with the anticipated studies that evaluate their system performance under combined environmental loads (wind, ice, temperature) that have often caused cascading failures and wide-spread blackouts that are difficult to recover from, improving safety across entire networks and cities.

- ***Sustainability***

Sustainability is a greater issue in European policies. Sustainable growth may be achieved, among others, by the promotion of steel as construction material that has a large potential for recycling. A safe and economic design for new lattice towers may thus significantly contribute to sustainable growth. Furthermore, a simple upgrade approach for existing steel towers may offer even higher benefits. Telecommunication towers frequently need to be strengthened due to increased loads from newer and larger antennas. Better exploitation of the member capacities also contributes to sustainability. It is worth mentioning that perhaps most lattice towers were built in the 1960s when electricity distribution expanded to cover most areas and telecommunication towers expanded - due to the advent of TV, radar communication etc. so that they have reached their notional design life and new towers will need to be designed as maintenance becomes an important issue. Renewable energy sources place considerable strain on existing power transmission capacities, necessitating a distributed, rather than centralized, power network concept, thus requiring the replacement and/or upgrading of multiple existing transmission lines to handle larger loads. High strength angles offer thus a high potential for sustainable rehabilitation of existing infrastructure, maximizing the in-place reuse of existing material, rather than its costly replacement. Alternatively, existing lattice tower members can be strengthened with the application of external CFRP strips, a method which can significantly prolong the life-cycle of out-of-date towers.

- ***European standards***

European standards such as for transmission towers are currently under review. Eurocodes are also under constant development and review. Working groups are being established to discuss comments and propose new rules. The project contributes to this development since it affects EN 1993-1-1, EN 1993-3-1 and EN 50341 whose rules should be complementary and consistent.

4.2 Outcome

The anticipated results of the ANGELHY project can be summarised in the following:

- Promotion of innovation in the design of steel lattice towers using high strength steel and large angle sections.
- Development of a new type of built-up member composed from two angles with different cross sections.
- Introduction of hybrid technologies in strengthening measures for lattice towers by application of FRP materials in angle sections.
- Enhancement of telecommunication and power transmission networks against the governing natural hazards in large parts of Europe.
- Improvement in life cycle costs and sustainability due to the reduction of collapses, extension of service life through upgrading of existing towers and the design of light-weight, yet reliable, new ones.
- Contribution to maintaining the market share for steel for tower construction, in view of the recent advances in precast reinforced concrete and pre-stressed concrete pylons (see, for example ASCE Manual of Practice MOP123, 2012). Potential enlargement of the market-share for steel via the introduction of long truss girders where angle sections can provide economical, lightweight and easily constructible solutions.

List of Figures

List of Tables

References

[1] EN 1993-1-1 (2005). Design of steel structures. Part 1-1 General rules and rules for buildings. Brussels. Comité Europeen de Normalisation (CEN).

[2] EN 1993-3-1 (2005). Design of steel structures. Part 3-1 Tower, masts and chimneys — Towers and masts. Brussels. Comité Europeen de Normalisation (CEN).

[3] EN 1993-1-8 (2005). Design of steel structures. Part 1-8 Design of joints. Brussels. Comité Europeen de Normalisation (CEN).

[4] EN 1990 (2002). Eurocode – Basis of structural design, Brussels: Comité Europeen de Normalisation (CEN).

[5] EN 50341 (2001). Overhead electrical lines exceeding AC 45 kV. Brussels: CEN/CENELEC.

[6] AISC (2000). Load and resistance factor specification for single-angle members. American Institute of Steel Construction, Chicago, IL.

[7] AISC (2003). Torsional analysis of structural steel members. American Institute of Steel Construction, Chicago, IL.

[8] Vayas, I., Charalambakis A., Koumousis V. (2009). Inelastic resistance of angle sections subjected to biaxial bending and normal forces. Steel Construction — Design and Research, 2, 138-146.

[9] Trahair, N. (2001). Bending, shear and torsion capacities of steel angle sections. Research Report R810, University of Sydney, Australia.

[10] Trahair, N. (2002). Biaxial bending of steel angle section beams. Research Report R822, University of Sydney, Australia.

[11] Trahair, N. (2003). Buckling and torsion of steel angle section beams. Research Report R833, University of Sydney, Australia.

[12] Rasmussen, K. (2003). Design of angle columns with locally unstable legs. Research Report R830, University of Sydney, Australia.

[13] Rasmussen, K. (2006). Design of slender angle section beam-columns by the direct stress method, Journal of Structural Engineering ASCE, 132(2), 204-211.

[14] Vayas, I., Dasiou, M.E., Danakali, I., Papageorgiou, M. (2008). Erdbebeneinwirkungen von Gebäuden mit aufgesetzten Masten. Bauingenieur 83(10), 432-439.

[15] Dasiou, M.E., Vayas, I., Efthimiou, E. (2010). Vergleichende Untersuchungen zur Windbelastung auf freistehende Telekommunikationsmasten nach DIN 4131 und Eurocode 3. Stahlbau, 79(1), 19-24.

[16] Kitipornchai, S., Lee H.W. (1986). Inelastic experiments on angle and tee struts. Journal of Constructional Steel Research, 6, 219-236.

[17] Marsh, C. (1997). Design of single and multiple angle columns and beams. Journal of Structural Engineering ASCE, 123, 853-856.

[18] Delesques, R. (1965). Solidarisation des cornières jumelées et des cornières en croix. Construction Métallique (CTICM), 4.

[19] Bureau, A., Chouzenoux, P.-L. (2010). Méthode simplifiée pour la vérification de barres comprimées composées de deux cornières assemblées dos-à-dos. Construction Métallique (CTICM), 4.

[20] Ciampoli, M., Petrini, F., Augusti, G. (2011). Performance-based wind engineering: towards a general procedure. Structural Safety, 33, 367–378.

[21] Cornell, C.A, Jalayer, F., Hamburger, R.O., Foutch, D.A. (2002). The probabilistic basis for the 2000 SAC/FEMA steel moment frame guidelines." Journal of Structural Engineering ASCE, 128, 526–533.

[22] Cornell, C.A., Krawinkler, H. (2000). Progress and challenges in seismic performance assessment. PEER Center News, 3 (2000) ⟨http://peer.berkeley.edu/news/2000spring /index.html⟩.

[23] Wang, Y., Rosowsky, D.V. (2013). Characterization of joint wind-snow hazard for performance-based design. Structural Safety, 43, 21–27.

[24] Zhang, L., Jaspart, J.-P. (2013). Stability of members in compression made of large hot-rolled and welded angles, Report, University of Liege.

[25] Beg, D., Rejec, K., Sinur, F. (2013). Determination of buckling curves for large angle profiles considering different steel grades and different residual stresses, Report, University of Ljubljana.

[26] Vayas, I., et al (2015). Verification of towers with L-sections under plastic design, Research Report National Technical University of Athens (in Greek).

[27] Nuño, J., Miller, M., Kempner, Jr., L. (2012). Historical perspective of full-scale latticed steel transmission tower testing. Electrical Transmission and Substation Structures, 313-322, doi: 10.1061/9780784412657.027

[28] Davies, D.K. (2010). North American tower failures: Causes and cures. Society of Broadcast Engineers (www.sbe.org).

[29] Fink, D., Beaty, W. (1978). Standard Handbook for Electrical Engineers 11th Ed., Mc Graw Hill.

[30] Moragiannis P. I. (2015). Experimental study of steel equal-leg angles strengthened with CFRP subjected to compression and to bending Diploma Thesis NTUA

[31] Colombi, P., Poggi, C (2006): An experimental, analytical and numerical study of the static behavior of steel beams reinforced by pultruded CFRP strips, Composites, Part B, 37 (2006) 64-63

[32] Deng J., Lee M.: (2007) Behaviour under static loading of metallic beams reinforced with a bonded CFRP plate, Composite Structures 78 (2007) 232-242

[33] Narmashiri, K et al (2011) Flexural strengthening of steel I-beams by using CFRP strips International Journal of Physical Sciences Vol 6 (7), 1620-1627

[34] Bambach MR et al. (2008). "Axial capacity and design of thin-walled steel SHS strengthened with CFRP." Thin-Walled Structures, doi:10.1016/j.tws.2008.10.006.

[35] Teng et al.(2012). "Strengthening of steel structures with fiber-reinforced polymer composites." Journal of Constructional Steel Research 78 (2012) 131–143

[36] Ben et al. (2014). "Compressive Strength of Uniformly Corroded Steel Angle Members Retrofitted with CFRP." ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 4, Issue 8, August 2014.

[37] Tamai H., Hattori A., Ozawa Y., Haitani T., Takamatsu T. (2012). "Design Formula for Rehabilitated Angle Steel Member Using Carbon Fiber Reinforced Plastic Plates." 15 WCEE, Lisbon 2012

[38] CNR-DT 202/2005: "Guide for the design and construction of externally bonded FRP systems for strengthening existing structures - Metallic structures", June 2007, Rome.