European Union
European Social Fund

HAMK
HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Proceedings of the METNET Seminar 2016 in Castellon

METNET Annual Seminar in Castellon, Spain, on 11 – 12 October 2016

Kuldeep Virdi and Lauri Tenhunen (Editors)

Editors:
Kuldeep Virdi, City, University of London
Lauri Tenhunen, Häme University of Applied Sciences (HAMK)

Proceedings of the METNET Seminar 2016 in Castellon

PRINTED
ISBN 978-951-784-784-1
ISSN 1795-4231
HAMKin julkaisuja 4/2016

ELECTRONIC
ISBN 978-951-784-785-8 (PDF)
ISSN 1795-424X
HAMKin e-julkaisuja 6/2016

PUBLISHER
Häme University of Applied Sciences (HAMK)
PO Box 230
FI-13101 Hämeenlinna, FINLAND
tel. +358 3 6461
julkaisut@hamk.fi
www.hamk.fi/julkaisut

Hämeenlinna, December 2016

INDEX

PREFACE

David Ricardo developed the theory of comparative advantage in 1817 (Ricardo, 1817). Ricardo stated that if two countries capable of producing two commodities do exchange the commodities in free market, then both countries would increase its consumption by exporting the goods for which it has a comparative advantage while importing goods from the other country. This assumes, however, that there exist differences in productivity between the two countries (Baumol & Binder, 2012).

Since 1817, economists have attempted to generalize the theory of comparative advantage in broader settings. In the case of many countries and many commodities, the theoretical examination of comparative advantage requires quite a complex quantitative formulation (Deardorff, 2005).

However, according to the new theory of international values, theory of comparative advantage can also be used to explain how global supply chains appear in general (Shiozawa, 2016).

Partly intuitively, the participants of METNET collaboration have utilised the benefits of comparative advantage now over ten years, starting from 2006 in Berlin, by changing constantly expertise and knowledge related to metallic construction and industries in Europe (www.hamk.fi/metnet). During the last ten years, METNET-network has actively promoted best practices and enabled transfer of knowhow between companies, research and training organizations at the European level. This collaboration has brought about many positive steps both in theory and in practice. For example, the networking participants have accomplished successful international projects with defined development targets. The participants continue to plan new collaborative activities and projects.

The METNET annual conferences and workshops have taken place in different countries and have been organised in cooperation with regional network members. The Department of Mechanical and Engineering Construction, Universitat Jaume I, Castellon, Spain, hosted the 11th METNET International Conference in October 2016. This Proceedings book presents the outcomes from the METNET Jaume seminar in 2016.

The first papers presented at the seminar concerned Moment-Rotation behaviour of welded High Strength Steel tubular columns. The main connection studied was between rectangular hollow section columns and beams. The paper from the Czech Technical University, Prague, explored the interaction between a steel arch and the membranes spanning between the arches. It was concluded that the tension in the membranes helped to increase the buckling load of the arch significantly, compared with the buckling load of an arch without any membranes.

A paper from Lapland University in Finland covered issues with the performance against wearing of ultra-high strength steels. Use of modern measurement techniques was described. Modelling of the behaviour using finite element analysis showed satisfactory correlation with experiments. An innovative technique for joining steel elements using adhesives was the topic of the paper from Brandenburg Technical University, Cottbus, Germany. An extensive range of topics covered in the research were described. Certain recommendations on the usability of different adhesives were made. Specifically, limits on the thickness of the adhesive and the effect of temperature have been determined. The research helps to remove reservations over the use of adhesives in steel connections.

The proceedings include short abstracts of some of the presentations made at the seminar. The wide range of research on steel and composite structures being done at the University of Catalonia, Barcelona, was described. The techniques used and the range of topics covered was truly extensive. The paper from University of Navarra described the need for a novel finite element, termed the cruciform element, to be used in non-linear frame analysis. The cruciform element has been implemented in analytical software. Very good correlation with more complex finite element modelling was demonstrated.

A paper on the stability analysis of circular hollow section columns, based on finite difference method was the topic of a paper from City, University of London. Good correlation with a large series of previously published experiments was obtained.

Two papers from the Laurea University of Applied Sciences in Finland covered a peep into the future. The first covered a framework for visionary concept designs for energy-efficient residential areas. The research, funded by European Regional Development programme, covered case studies from 3 regions in Finland. Another paper presented results from a survey in Finland on the current and future use of clean technologies. A list of key actors who are playing significant roles in developing solutions. Interestingly, the audience was used for collecting more data for the survey. One of the conclusions was that bureaucracy needs to be reduced at all levels, although how this was to be achieved was still an open question.

Two presentations dealt with current research grant applications – one dealing with sandwich panels and the other with connections between rectangular hollow sections and I-beams. Due to reasons of confidentiality, the papers have not been included in the proceedings.

Kuldeep Virdi and Lauri Tenhunen

REFERENCES

Baumol, William J. and Alan S. Binder (2012). Economics: Principles and Policy. Mason, USA.

Deardorff, A. V. (2005). "How Robust is Comparative Advantage?" Review of International Economics. Volume 13 (5): 1004 – 1016.

METNET (2016). METNET Ideas. www.hamk.fi/metnet

Ricardo, David (1817) On the Principles of Political Economy and Taxation. London.

Shiozawa, Y. (2016). The revival of classical theory of values. In Nobuharu Yokokawa et als. (Eds.) The Rejuvenation of Political Economy, May 2016, Oxon and New York: Routledge.

STABILITY OF A STEEL TUBE ARCH SUPPORTING BARREL TYPE TEXTILE ROOF MEMBRANES

Ondrej Svoboda
Czech Technical University in Prague
Thakurova 7, Prague 6, Czech Republic

Josef Machacek
Czech Technical University in Prague
Thakurova 7, Prague 6, Czech Republic

ABSTRACT

Following extensive tests of a single (alone) built-in tubular steel arch and the identical arch supporting textile membrane roofing fastened to the arch, the corresponding numerical analyses are presented. The membranes made of the prestressed PVC coated polyester fabric Ferrari® Précontraint 702S were used as a currently standard and perfect material. The tests and results oriented to the loss of in-plane and out-of-plane stability of the arch are briefly described. SOFiSTiK software was employed to model orthotropic membrane and supporting steelwork behavior using geometrically nonlinear 3D analysis with imperfections (GNIA). The numerical results were validated using test data based on various membrane prestressing with excellent agreement. Finally results of vast parametric studies concerning stability of a central arch in five arches membrane assemblies are presented. Enormous savings in the tubular steel arches due to the membrane supporting effects are revealed, leading to omission of a stability check concerning the out-of-plane arch buckling.

INTRODUCTION

Tensioned Fabric Structures (TSF) are becoming popular for their visual appearance, lightness and sufficient load-bearing capacity. Currently various membrane materials are available for both single layer double curved shapes (barrels, hypars, cones) and double/more layer pneumatic constructions (inflatable cushions, air supported pneumatic structures). The PVC coated polyester fabric (e.g. Précontraint FERRARI®) seems to be a rational choice for common single layer structures with the lifetime up to 20 years, acceptable cost and good joining possibilities (welding or sewing). Details on other materials as glass fabrics, expanded PTFE, polyethylene fabrics, ETFE, THV are described e.g. by Svoboda & Macháček (2015) or Macháček & Jermoljev (2016).

Design of structures with TSF requires geometrically and materially non-linear analysis with imperfections (GMNIA). In the analysis an appropriate input of the membrane material behaviour is required. The material is due to its structure non-homogeneous, orthotropic (warp and fill directions) and non-linear. Based on experimental investigation, Kato et al. (1999) suggested a numerical model requiring 15 data parameters. The model proved an excellent agreement with tests but is rather too complicated for a practical use. Apart from a simplified approach, Gosling 2007 suggested “strain-strain-stress” approach using response surfaces linking strains to stresses through three dimensional representations. A non-linear material model with 5 parameters based on tests and depending on load ratios in warp and fill direction was proposed by Galliot and Luchsinger (2009). Model parameters are: warp and fill Young’s modules for the respective load ratio 1:1, the change in warp and fill Young’s modules (variation of the moduli on the whole range of load ratios) and the Poisson’s ratio. A simplified stress-strain model for coated plain-weave fabrics was developed by Pargana and Leitao (2015). The model consists of three nonlinear elements to model the yarns and an isotropic plate to model the coating.

Nevertheless, in accord with recommendation of Tensinet Analysis & Materials working Group (Foster & Nollaert 2004) a simplified elastic approach may be employed using the simple plane stress theory. The supplied test data provides elastic modules for warp and fill directions and corresponding Poisson’s ratio, valid for anticlastic type of structures. Recently Uhlemann et al. (2015) analysed two approaches concerning simplified elastic constants for design of the membranes (Japanese MSAJ and acc. to European Tensinet & Materials working Group) and found the European approach more general and reasonable for PES/PVC material, but still with reservations.

For novel unique structures the use of supporting components as slender as possible is necessary to follow the concept of a delicate, light and attractive structure with the membrane surface and to avoid any visual intervention of supporting steelworks into the membrane area. While membrane surface is exclusively tensioned, supporting construction is most often exposed to a compression and/or bending. This type of loading, in combination with slender elements, results into stability problems and design must be done with respect to these effects. Different situations occur, when membrane surface is joined with the supporting steel structure continually. In this case the membrane represents a spring support for the supporting structure, the critical (buckling) length of individual steel elements is changing, and both parts of the entire system cannot be investigated separately but as one complex structure using proper software package which allows integrated modelling and computing (e.g. EASY (technet), FORTEN (ixForten), SOFiSTiK, Rhino Membrane, NDN (membrane NDN)], etc.). Detailing of membrane structures and erection methods are well described by Seidel (2009), and the basic design in European Design Guide (2004).

The paper deals with stabilizing effects of membranes to the respective supporting steelwork, based on numerical parametrical studies validated by tests. The tests relate to the structural model representing a concert stage structure with two supporting arches. The stability of the inner supporting arch is of the primary interest. Influence of various membranes prestressing on the structure stabilization is analysed and compared with the test results. Parametrical study concerns nonlinear behaviour of tube arches with various geometries which support textile membranes.

LABORATORY TESTING

Model Arrangement

Model of an outdoor covered stage (with an approx. reduction 1:10) was proposed using Formfinder Software. The software enables intuitive manipulation with membrane shapes under required stress level in interactive way and export/ import to other programs through DXF/DWG files. Supporting steelwork involves two supporting arches (outer and inner CHS tubes), bottom edge steel wire ropes and membrane plates, see Figure 1.

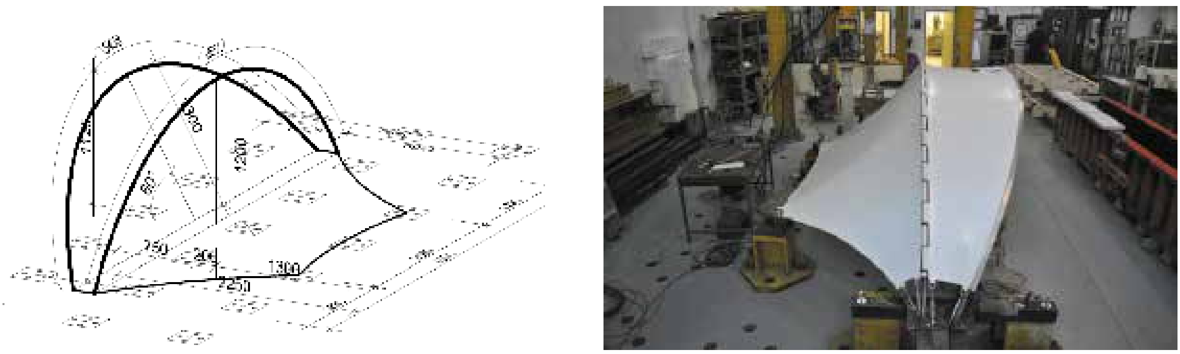


Figure 1: Setup and photo in laboratory.

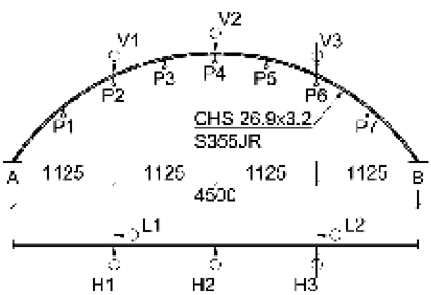
The membrane is PVC coated polyester fabric Ferrari® Précontraint 702S with opaque surface (weight 830 g/m²). Dimensions of the vertical inner tube arch are LxH = 4500x1200 [mm] and outer tube arch has inclination of 60° in respect to horizontal.

The fabric of Serge Ferrari group is made of polyester scrim coated both sides with liquid PVC and PVDF topcoat, weldable for joining. The material is due to its structure non-homogeneous, orthotropic (warp and fill directions) and non-linear, with elastic constants presented further at chapter of numerical modelling. Nevertheless, the patented fabrication process ensures similar elongation behaviour in both warp and fill directions and minimum creep. Concerning material characteristics the biaxial test performed by Lab BLUM Stuttgart 2005 is available. With respect to these tests both warp and fill braking loadings were considered as $S_{ult} \approx 56$ kN/m, while working loading $S_{max} = S_{ult}/5 \approx 11.2$ kN/m to exclude tearing and prestressing up to $P = S_{max}/5 \approx 2.24$ kN/m. Nevertheless, prestressing in the case of the lab model was up to $P \leq 0.5$ kN/m only.

The steel tubes from grade S355J0 were hot-formed in workshop. The investigated inner tube of ø 26.9x3.2 [mm] and outer one of ø 88.9x3.2 [mm] were welded to steel blocks to form a fixed-in frame acc. to Figure 1. Coupon tests of the inner steel tube resulted into average yield strength f_y = 475 MPa, ultimate strength f_u = 595 MPa and elongation 27.1 %. Modulus of elasticity was considered in accord with Eurocode 3 as E = 210 GPa.

The membrane was fastened to the outer tube arch using riveted aluminium keder profile and to the inner tube using alternating pockets. The standard 7x7 wire peripheral rope with diameter of 6 mm inserted in a curved cuff fastened the membrane to corner plates and anchors. Deflections of the investigated inner arch were measured using transducers (electrical potentiometers) in vertical (V), transverse (H) and longitudinal (L) directions in positions as shown in Figure 2, together with loading points (P). In supports and midspan were located strain gauges denoted (T), always in four mutually perpendicular positions.

The membrane cut resulted from EASY (technet) software, considering uniform prestressing of roughly P = 0.5 kN/m. During assembly the peripheral ropes were tightened and the membrane checked against wrinkling. Eight strain gauges were placed at various locations within the membrane surface for rough information on prestressing values. The measuring before and after prestressing resulted into average prestrain value of ε_y = 140 μm/m (i.e. $P \approx$ 0.09 kN/m) in perpendicular direction with respect to the supporting arches and ε_x = 450 μm/m (i.e. $P \approx$ 0.30 kN/m) in parallel direction to the arches.



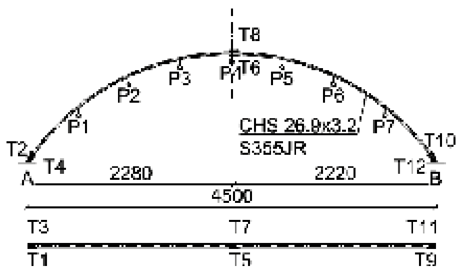


Figure 2: Positions of loading (P), transducers (V, H, L) and strain gauges (T).

Test Results

The investigation concerned exclusively the inner steel arch to find stabilizing effect of the membrane to its nonlinear behaviour. First the inner arch alone (without fastening the membrane) was loaded and second, after the membrane assembly, the complete membrane structure. For loading calibrated pouches with steel pellets were used and suspended from seven given points P at the arch. The loadings were carefully arranged to simulate uniform symmetrical loading and asymmetrical loading corresponding to the first in-plane buckling mode. Maximum loadings for arch alone are given in Figure 3, for complete membrane structure in Figure 4.

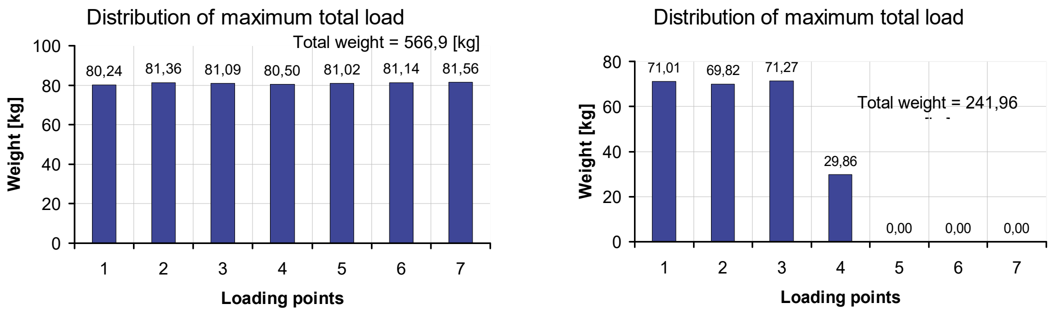


Figure 3: Loading of the inner steel arch alone: Left - symmetrical, right - asymmetrical.

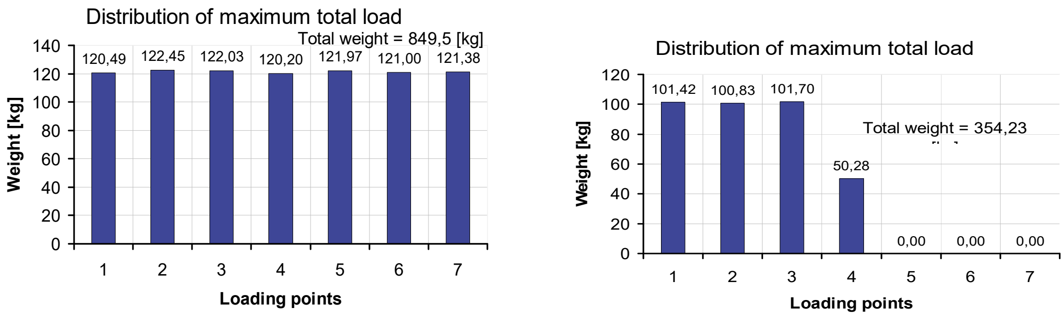
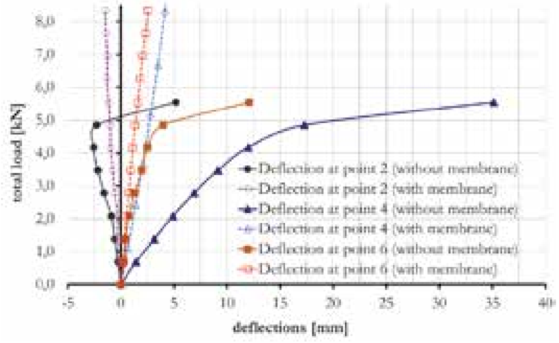


Figure 4: Loading of the arch joined with the membranes: Left - symmetrical, right - asymmetrical.

Individual loading steps amounted for roughly 1/10 of maximum loading, each followed by unloading. The tests were terminated when abnormal deflections out-of-arch plane or in-arch-plane were reached.

Results for Symmetrical Loading

Deflections of the inner arch under increasing loading in vertical and horizontal directions are shown in Figure 5 (unloading is not included and generally was fully elastic). The arch without membrane buckled out-of-plane at total loading approaching F_0 = 5.5 kN, with associated vertical deflection along all span down. On the other side the test with arch stabilized by the membrane was terminated under total load of F_M = 8.3 kN, showing very small and nearly linear increase of the mid span deflection. Stabilizing effect of the membrane is enormous.



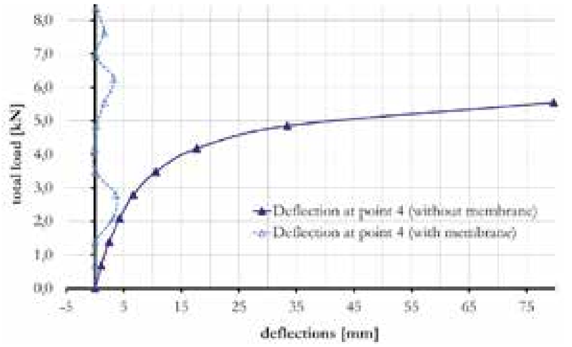
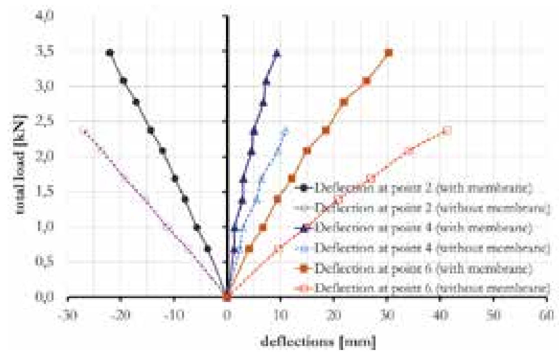


Figure 5: Symmetrical loadings: Vertical deflections (left), transverse deflections (right).

Results for Asymmetrical Loading

Vertical and transverse horizontal deflections under increasing loading are shown in Figure 6. Testing of the arch without membrane ("0") terminated under total loading F_0 = 2.37 kN, giving maximal vertical deflection δ_0 = 41.3 mm and horizontal one η_0 = 3.5 mm. The arch stabilized by membrane ("M") deflected much less, giving for the same loading $F_M = F_0$ = 2.37 kN values δ_M = 18.5 mm and η_M = 0.5 mm. The stabilizing effect of the membrane concerning vertical deflection resulted into reduction of 45 %.Difference comparing vertical deflections in positions V1 and V3 (see Figure 2) gives $\Delta\delta_0$ = 68.3 mm and $\Delta\delta_M$ = 32.9 mm.

Measured displacements and stresses (not presented) prove expected enormous effect of the membrane on buckling load and strength of inner supporting arch, particularly in asymmetrical loadings. Test values are used for validation of numerical analyses.



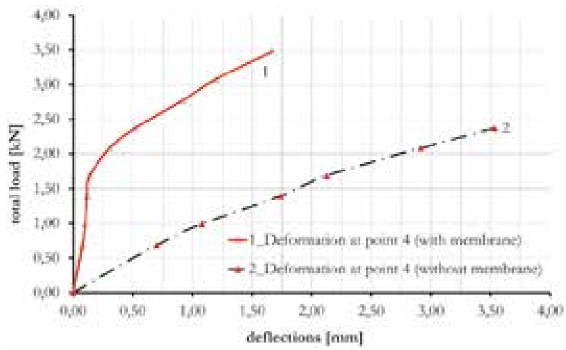


Figure 6: Asymmetrical loadings: Vertical deflections (left, positive down), transverse deflections (right).

NUMERICAL ANALYSIS

Numerical Model and Validation by Tests

SOFiSTiK software 2014 was used to perform GNIA (using N-R iteration) both for the inner arch alone and the complete membrane structure. Various meshing of the membrane was analysed (square sizes of 25, 50, 100 and 200 [mm]) giving nearly identical stress results (differences ≤ 0.2%), but with increase of computer time between largest and least mesh up to 107 times. Therefore, optimum mesh with 50 mm size was used throughout the analysis.

Arch Alone Analysis

The tube arch was introduced as ø 26.9x3.2 [mm], with built-in supports, material S355J0 and Young's modulus E = 210 GPa. Initial geometry as measured was introduced into analysis (theoretical radius R = 2709 mm with out-of-plane (transverse) deflection at the crown w_0 = 17 mm). The elastic buckling analysis of the perfect arch under symmetrical loading in accordance with Figure 3 (left) resulted into total critical loads $TL_{cr,1}$ = 6.7 kN (out-of-plane single wave buckling), $TL_{cr,2}$ = 15.4 kN (out-of-plane two waves buckling), $TL_{cr,3}$ = 18.7 kN (in-plane two waves buckling), etc.

GNIA transverse deflection curves for symmetrical loading are shown in Figure 7 left, indicating the first out-of-plane bifurcation earlier but in accordance with test, roughly at 4.9 kN. Vertical deflections for asymmetrical loading correspond also well to test results, see Figure 7 right.

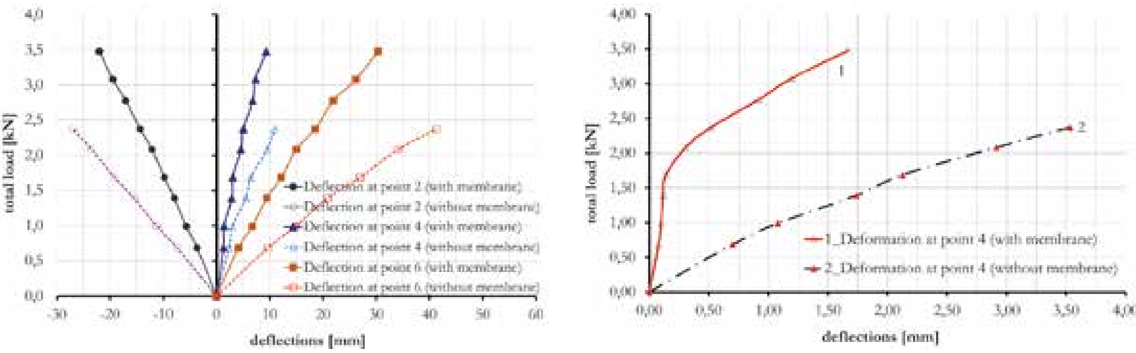


Figure 7: Arch alone, test and GNIA results. Left: transverse deflections for symmetrical loading at midspan. Right: vertical deflections for asymmetrical loading.

Full Membrane Structure Analysis

The membrane FERRARI® 702 was considered with linear elastic orthotropic behaviour taking account for influence of load ratios according to Galliot and Luchsinger 2009. The necessary five parameters were taken as: warp and fill Young's moduli for 1:1 load ratio $E_w^{1:1} = 635.3$ kN/m and $E_{wf}^{1:1} = 661.9$ kN/m, the change in warp and fill Young's moduli $\Delta E_w = 295$ kN/m and $\Delta E_f = 168$ kN/m, the Poisson's ratio $\nu = 0.196$. The warp direction was considered as perpendicular to the arch plane and conversion to stresses due to approximate thickness of the membrane as 0.7 mm.

Initial geometrical imperfections of the arch were measured just before the first loading and were found to be 5.0 mm in horizontal direction at the top of the arch and +/-10.0 mm in vertical direction at the quarters of the arch. Initial shape of the membrane surface was generated automatically by the AutoCAD as a surface with minimal area. The shape was exported into SOFiSTiK software. For each level of the membrane prestress the corresponding value of the perimeter cable pretension was received from formula:

$$S_S = r \cdot S_M \tag{1}$$

where S_S is a tension force in a perimeter cable [kN],
r radius of the cable curvature [m],
S_M prestress in the membrane perpendicular to the cable [kN/m].

The equilibrium state and final unloaded shape of the structure was found under initial SOFiSTiK software calculations. The results of GNIA under various pretension of the membrane P [kN/m] is shown in Figure 8. The level of pretension is the crucial parameter for the arch stability and resistance capacity. Higher pretension in membrane logically means higher stability and smaller deflection of the investigated arch. It should be recalled, that the real pretension during the testing was influenced by the alternating “pockets” connection of the membrane to the inner arch and due to this fact rather non-uniform and slacked. As mentioned, the randomly measured values during the test at several localities (which however can't be considered as a reliable ones), were between 0.09 and 0.3 [kN/m]. This is reflected in numerical analysis with pretension close to zero (0.2 kN/m) which provides results very near to the test ones. Therefore, the received GNIA results with the corresponding prestress 0.2 kN/m justify use of the model for following parametric studies.

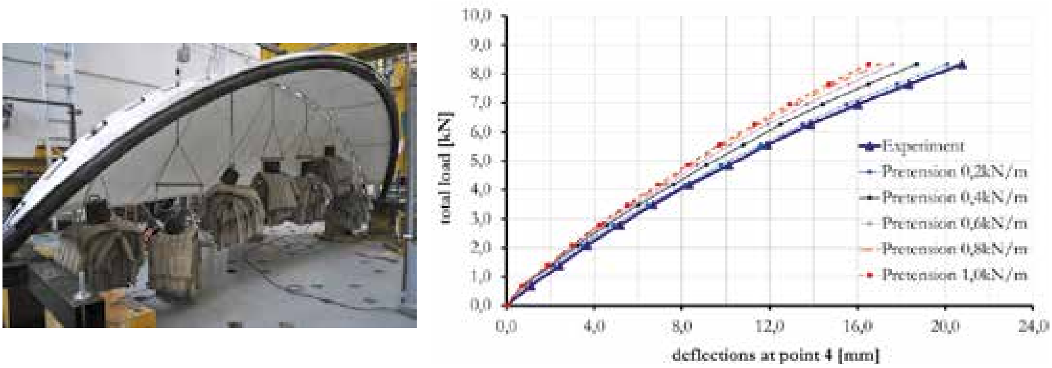


Figure 8: Symmetrical loading of the membrane model: Comparison of the test and GNIA vertical deflections under various pretension.

Parametrical Study

The principal goal of the study was to determine the stabilizing effect of common textile membranes on buckling and nonlinear behaviour of slender steel supporting arches. Both in-plane and out-of-plane arch buckling was studied for various geometries of arches and membranes in a parametrical study. Inner arches in the 5 arch assembly with practical dimensions arranged in a barrel type structure in according with Figure 9 were investigated. To evaluate the influence of lateral boundary conditions, the outer (edge) arches were either flexible (supported by a truss) or continuously fixed in all three directions.

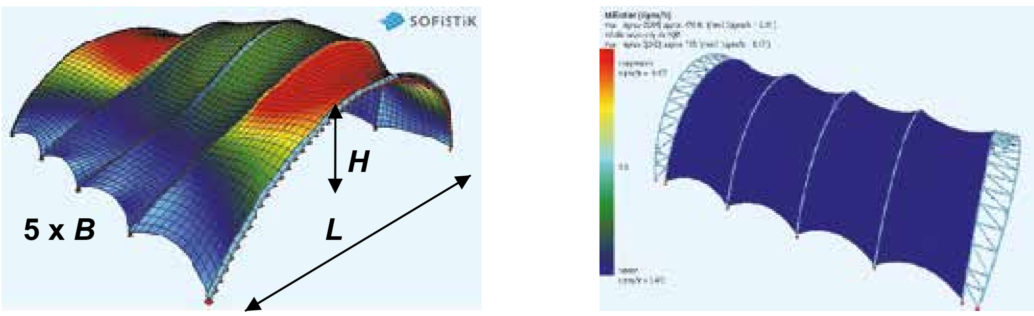


Figure 9: Five arch assembly and outer lateral flexible support.

The study covers arch spans of $L = 6 \div 20$ [m], rise $H = L/10 \div L/2$ and spacing of the five arches $B = 3 \div 10$ [m]. Loading was considered in vertical direction (alternatively in radial direction) as 1 kN/m^2 simulating snow loading only, together with various prestressing of the membranes, ranging from 4 to 7 kN/m in both directions. The arch dimensions were designed for resulting internal forces according to Eurocode 3 from steel grade S355 in an iterative way, to reach 80÷90 % of their design capacity.

First the buckling of the arch alone with built-in supports was investigated to find in-plane and out-of-plane buckling loads under considered loading (Figure 10).

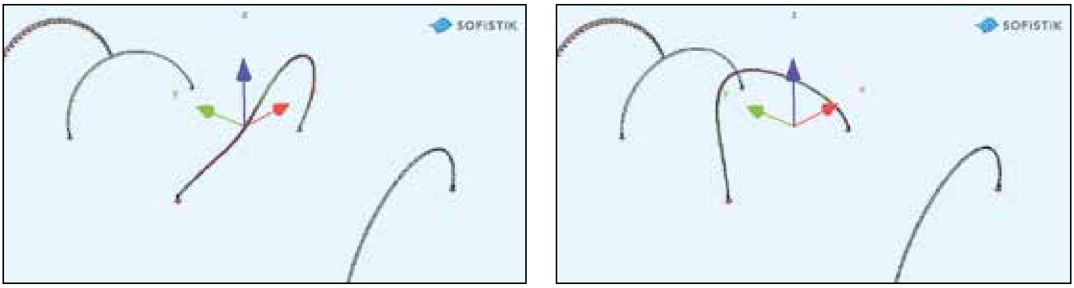


Figure 10: Arch alone: in-plane buckling (left), out-of-plane buckling (right).

Second the all five arch assembly (including lateral support) was analysed to find in-plane and out-of-plane buckling loads for the mid-arch under loading including various prestressing of the membranes (Figure 11).

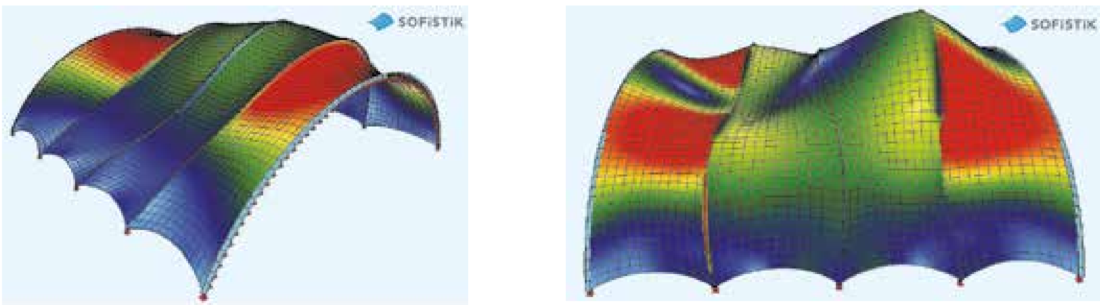


Figure 11: Arch with membranes: mid arch in-plane buckling (left), mid arch out-of-plane buckling (right).

For example tube arch ø 133x5 [mm], steel grade S355, with L = 12 m, H = 3.6 m and B = 3 m and uniformly loaded vertically under 3 kN/m with mesh size 250 mm, gives following buckling loads: arch alone in-plane buckling $N_{cr.y}$ = 189 kN, out-of-plane buckling $N_{cr.z}$ = 70 kN; arch with membranes under vertical loading 1kN/m^2 and prestressed by $P \approx 5.0$ kN/m gives $N_{cr.y}$ = 346 kN and $N_{cr.z}$ = 542 kN. Similar relations were obtained throughout the parametrical study, indicating that the membrane support to the stability of arch is substantial.

CONCLUSIONS

The main conclusions are:

1. Tests confirmed decisive effect of textile membranes on both in-plane and out-of-plane supporting arch stability and strength.
2. GNIA with linear elastic orthotropic behaviour of the textile membrane and using SOFiSTiK software proved to be adequate for numerical modelling.
3. The real value of the membrane prestressing substantially influence the deflections and strength of the supporting arch structure (see Figure 8).
4. Parametric studies of large barrel membrane structures supported by a row of steel arches resulted into huge savings in a practical design of supporting steel arches due to enormous increase of both in-plane and particularly out-of-plane buckling loads in comparison to the ones of an arch alone (e.g. in the shown case $N_{cr.z}$ increased 7.7 times), mentioned already by Svoboda and Macháček 2016.
5. Within the scope of the parametric study for the tube arch alone the in-plane buckling of the arch is not decisive ($N_{\mathrm{cr.in}} \approx 2 \div 4\, N_{\mathrm{cr.out}}$), while for the arch with membranes the out-of-plane arch buckling is not decisive ($N_{\mathrm{cr.out}} \approx 2 \div 3\, N_{\mathrm{cr.in}}$).

ACKNOWLEDGEMENT

The support of the grant GACR No. 105/13/25781S is gratefully acknowledged.

REFERENCES

Formfinder Software GmbH, Wien. http://www.formfinder.at/main/software.

Foster, B. Mollaert, M. (2004): European Design Guide for Tensile Surface Structures, TensiNet, 354 p.

Galliot, C., Luchsinger R.H. (2009): A simple model describing the non-linear biaxial tensile behaviour of PVC/coated polyester fabrics for use in finite element analysis. Composite Structures, Vol. 90, No. 4, pp. 438 – 447.

Galliot, C., Luchsinger, R.H. (2009): Non-linear properties of PVC-coated fabrics used in tensairity structures. Proc. ICCM17, Edinburgh, 10 p.

Gosling, P. (2007): Basic philosophy and calling notice. Tensinet analysis & Material working group, Tensinews (www.tensinet.com), No. 13, pp. 12 – 15.

ixForten 4000. http://www.ixforten.com/

Kato, S., Yoshino, T., Minami, H. (1999): Formulation of constitutive equations for fabric membranes based on concept of fabric lattice model. Eng. Structures, Vol. No. 8, pp. 691 – 708.

Laboratorium BLUM Stuttgart (2005): Report on biaxial tests Précontraint 702. http://arc-ae.net/ARC1010-Pisco/.

Machacek, J., Jermoljev, D. (2016): Steel structures in interaction with non-metallic membranes, J. Civil Engineering and Management doi: 10.3846/13923730.2015.1128482.

membrane NDN software. http://www.ndnsoftware.com/.

Pargana, J.B., Leitao, W.M.A. (2015): A simplified stress-strain model for coated plain-weave fabrics used in tensioned fabric structures. Eng. Structures, Vol. 84, pp. 439 – 450.

Rhino Membrane. http://www.membranes24.com/rhino-membrane.html.

Seidel, M. (2009): Tensile Surface Structures - A Practical Guide to Cable and Membrane Construction, John Wiley & Sons, 240 p.

SOFiSTiK 2014. http://www.sofistik.de/.

Svoboda, O., Macháček, J. (2015): Behaviour of steel arch stabilized by a textile membrane, 2nd Int. Conf. on Innovative Materials, Structures and Technologies, IOP Conf. Series: Materials Science and Engineering 96, pp. 1 – 8, http://iopscience.iop.org/article/10.1088/1757-899X/96/1/012055/pdf.

Svoboda, O., Macháček, J. (2016): Tubular steel arch stabilized by textile membranes, J. Advances in Technology Innovation (AITI), Vol. 1, No. 2, pp. 50 – 52, http://ojs.imeti.org/index.php/AITI/article/download/180/315

technet gmbh Berlin-Stuttgart. http://www.technet-gmbh.com.

Uhlemann, J., Stranghöner, N., Saxe, K. (2015): Stiffness parameters for architectural fabrics: An analysis of two determination procedures. Structural Engineering International, Vol. 25, No. 1, pp. 9 – 19.

BONDING TECHNOLOGY IN STEEL STRUCTURES

A SUMMARY OF RESEARCH ACTIVITIES AT CHAIR OF STEEL AND TIMBER STRUCTURES

Yvonne Ciupack and Hartmut Pasternak
Chair of Steel and Timber Structures, Brandenburg University of Technology, Cottbus, Germany

ABSTRACT

Bonding technology is an innovative alternative to typical joining methods in steel structures. For more than 10 years studies have taken place at the the Chair of Steel and Timber Structures on the potential of bonded steel joints within the scope of various research projects, which are presented in this paper. Two new application examples for façade construction are currently being investigated. For these structures constructive solutions, mechanical models, design rules and testing procedures for cyclic loading were developed. The efficiency of refurbishment measures made with bonded CFRP laminates is a second research field of the Chair. The future work will focus on long-term effects and cyclic loading of bonded steel joints.

INTRODUCTION

The joining technology plays an essential role in steel structures. It influences the costs of manufacturing and erection as well as the quality of execution. The requirements on joining techniques affect the static and dynamic carrying capacity, the safety and reliability, the geometric precision as well as aesthetics and durability. The application of traditional joining methods is limited regarding the cross section reduction through drilled holes, the residual stresses through welds and the fatigue strength through notch effects together with aesthetic reasons. As an alternative to welding and bolts, the bonding technology provides considerable advantages for this requirement profile.

Bonded joints are successfully used in other industries, e.g. automotive and aviation. Despite many technical developments and improved long-term resistance of adhesives, there is no noteworthy example of application of adhesive bonding in structural engineering.

The Chair of Steel and Timber Structures investigates the innovative bonding technology within the scope of different research projects, some of which are presented in this paper.

DEVELOPMENT OF NEW APPLICATIONS OF BONDING TECHNOLOGY

In a first research project (Dilger *et al.* 2008) two different application examples of bonded steel joints in steel façades were developed. With these constructions a research unit was created, which still functions and has been expanded during recent years. Examples of a bonded façade connection and façade reinforcement will be presented in the following.

Bonded façade connection

Trapezoidal façades are used especially for industry halls. Commonly, the connection of a trapezoidal sheet with the support structure is realized with self drilling screws. Thus, the cross section of structural elements is reduced in the region of the joint, which leads to a decreased load carrying capacity and stress concentration. This detail means degradation, particularly for the fatigue limit strength of the construction. This unsatisfactory situation can be prevented by using bonding technology. By bonding the trapezoidal sheets to the support structure with the assistance of modified connection profiles, the cross section reduction can be avoided.

Such an alternative joining method does not only provide an advantage regarding the carrying capacity, but also improves the aesthetics of the façade view by avoiding visible fastener heads. Errors, dents or scratches, which can occur during the mounting, are avoided. Besides, an essential benefit is the preservation of the self cleaning effect of the façade through the absence of screws at the outer shell.

It is necessary to abide by the rules for bonding-suitable construction, in order to successfully establish this innovative façade joint. The connection is designed so that the complete bonding process can be realized under defined conditions in a laboratory. Thus, a specially shaped connection profile is required. Different design variants for the bonded façade connection are shown in Figure 1(a).

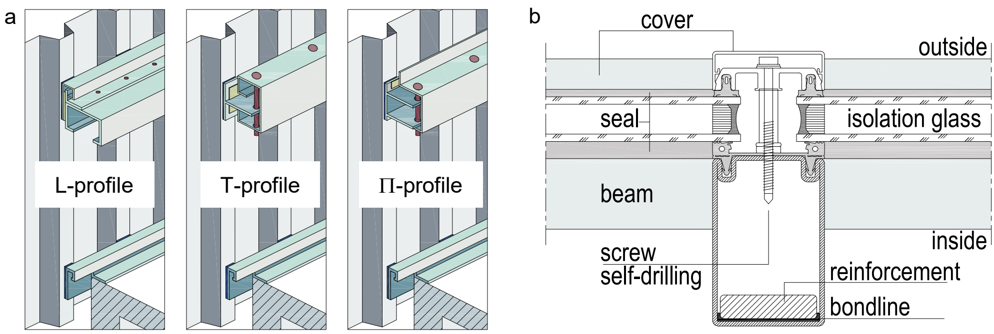


Figure 1: (a) Structures for bonded façade connections with different shape of connection profile; (b) Bonded façade reinforcement

Bonded façade reinforcement

The modern city panorama is defined by glass façades and slender structural components. Architects and builders demand high side view transparency, as well as segmented and wide opened façades. Therefore, transom-mullion façades are often realized.

With this construction, the wind loads are transferred from the outer shell to the mullion profiles, which induce the forces on to the transom profiles at certain points. This way, the transom profiles are stressed by bending moments and transfer the loads to the foundations.

To ensure the required side view transparency, small transom profiles need to be used, which can be arranged with high distances in-between. Thus, a reduction of the cross section dimensions, as well as reduction of profile stiffness and carrying capacity is required simultaneously. For hollow profiles, one possible solution can be found by using sections with thicker profile walls. In contrast, this kind of element is produced with a cold forming process, which is limited to certain sheet thicknesses. The bonding technology provides an innovative and simple alternative. With the application of an inner reinforcement, as shown in Figure 1(b), the transom stiffness can be increased without changing the outer dimensions. This new compound cross section shows an increased carrying capacity compared with typical façade profiles and allows the retention of common mounting methods on site. The bonding process is conducted by means of a pneumatic method in a laboratory.

The pre-assembled profile will be connected with the mullion elements on site by use of dowel type fasteners. Such kind of façade structure provides high transom distances with slender profiles, so that the construction meets the requirement of side view transparency.

The principle of a hollow façade profile with bonded inner reinforcement is comparable to the carrying behaviour of glued laminated timber. That means, a composite section is created to increase carrying capacity and stiffness. In contrast to timber structures, the stiffness of the compound steel elements is so high, that a proof of the bondline could be decisive. This fact should be considered in a design model.

DESIGN RULES FOR BONDED STEEL JOINTS

For the definition of design rules, according to the standards, mechanical models are essential for the description of the bondline behaviour. In the scope of different research activities (Dilger *et al.* 2008, Meinz 2010), two design models for the mentioned application examples were developed. The fundamental ideas of these resistance models will be presented in the following sections.

Design of bonded façade connection

For the design of bonded façade connections an analytical model is used, based on the weakest-link-theory. The essential mode of failure can be identified by comparing the failure modes of the joint components. These are the connection profile, the bondline and the trapezoidal sheet. The resistance of the whole joint can be expressed as the smallest resistance of its components.

Based on the theory of elastically supported slabs, Meinz (Meinz 2010) developed a design approach for the prediction of the bondline resistance. Therefore, the joint is divided into partial models for every supporting direction. A superposition of these partial models at the end of the design procedure provides the three-dimensional system and the complex stress distribution in the bondline. The principle of the design concept is shown in Figure 2.

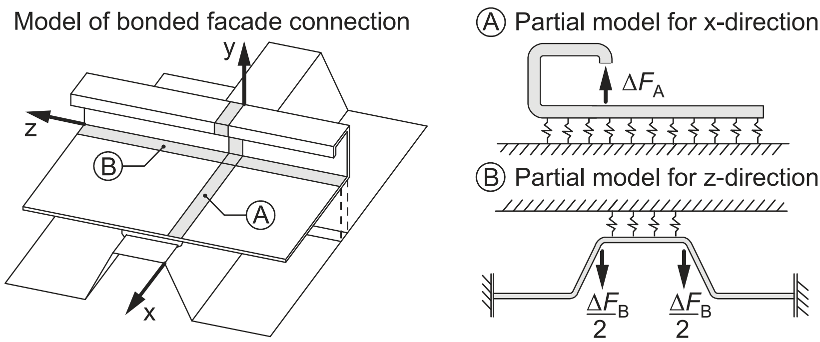


Figure 2: Model for the bonded façade connection

Design of bonded façade reinforcement

The concept for the design of bonded façade reinforcement is structured, so that the composite section is formed by the partial cross section of the reinforcement profile and the hollow profile. The first step is the test of a quasi-rigid compound. Therefore, a dimensionless shear-effect-value is introduced and deduced from the differential equation of beam deflection and joint displacement for semi-rigid compound. If this test has been met, a comparison of the bondline strength with the determined stresses follows. To describe the complex stress distribution in the bondline a procedure is included which is based on the theory of elastically supported slabs. This procedure is equivalent to the method for bonded façade connections. To take into account the concentrated load introduced at the joints between the transom and mullion profiles, effective lengths are determined based on numerical studies for different connection details of typical façade joints.

Model calibration

In a further project (Pasternak 2012), the presented models were calibrated aiming at the development of a general procedure of concept calibration for bonded steel joints. Basis for the calibration process is a description model for the prediction of the resistance which contains stochastic and deterministic parameters. A comparison of test result with model results is the essence of the method.

To determine characteristic material properties of a bondline based on Eurocode, so-called butt joint tests (DIN EN 15870) and shear lap tests (DIN EN 14869) were carried out. The results for tension strength (σ_k), shear strength (τ_k), Young's modulus (E_k) and shear modulus (G_k) are summarized in Table 1.

Table 1: Characteristic material properties of adhesives [N/mm²]

Adhesive basis	σ_k	τ_k	E_k	G_k
MS polymer	1.31	1.32	5.64	0.54
Epoxy	38.7	29.3	3063	308.9

In the next step, investigations focused on specimen component tests for the application examples. The test setup needed to ensure that a failure of the bondline can be observed. A general requirement is the warranty of a cohesive failure, which can be met by specific surface pre-treatments, e.g. blasting, of the steel components being connected. Figure 3 shows the test setup and some results for the first application example.

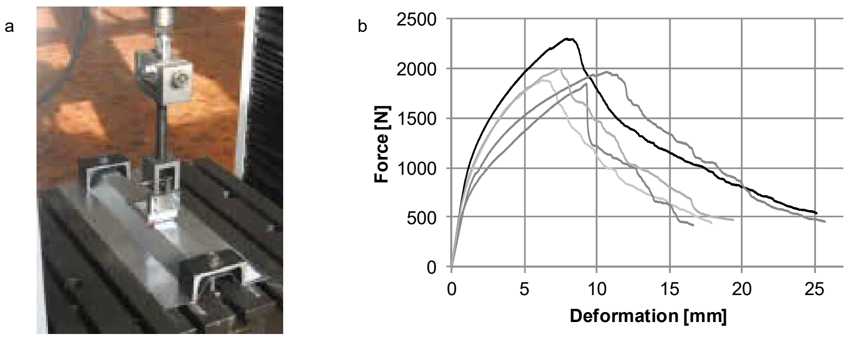


Figure 3: (a) Test setup; (b) Test results

The essential task of the bonded façade connection in the mounted state is the transfer of wind loads to the support structure of the façade. The critical wind suction loads are considered in the tests, because bondlines react more sensitive to tension loads than to compression. The specimen was modelled to be one corrugated segment of a 500 mm long trapezoidal sheet. For the bonding procedure a silane modified adhesive (MS polymer) was used, because it behaves elastically (see Table 1) and thus a deformability of the joint was ensured. The load introduction occurred perpendicular to the joint with a testing rate of 2 mm/min to create a quasi-static stress state in the bondline. For all specimen tests a cohesive failure of the bondline could be achieved and a strongly non-linear behaviour was observed.

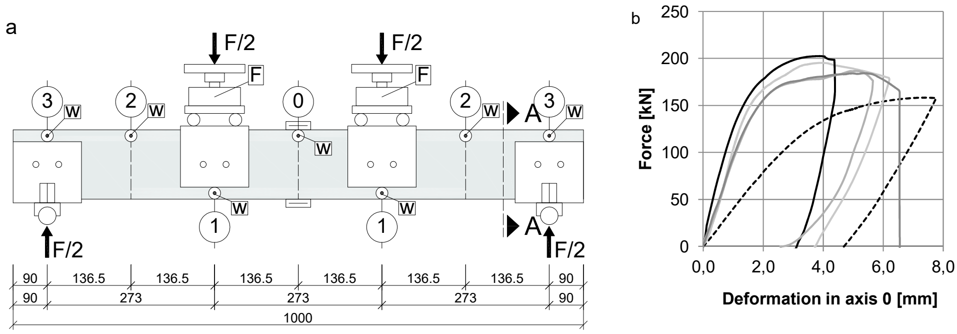


Figure 4: (a) Four point bending test; (b) Test results.

To investigate the reinforced façade profile, four point bending tests on a 1 m hollow section with inner steel reinforcement were carried out (Figure 4). The compound between the components being joined was made by an epoxy adhesive. Through the high stiffness of this kind of adhesive (see Table 1) a quasi-rigid compound can be assumed. The real loading situation in the mounted state was modelled in tests with a load introduction into the specimens at bolted connections. A cohesive failure of the bondline due to restoring forces at the profile ends could be registered for all tests. A significant improvement of profile stiffness could be achieved compared to a reference façade transom without reinforcement (dashed line in Figure 4).

Based on Eurocode (DIN 1990) the model calibration was realized in a final step of the research. The results are partial safety factors for the design of the mentioned application examples of bonding technology. For the bonded façade connection, a factor of $\gamma_M = 2.2$ was found and for the façade reinforcement, $\gamma_M = 1.6$.

Conversion factors

The objective of implementing conversion factors is to enhance the design model with the result that the resistance can be modified with the following equation.

$$R_d = \frac{R_k}{\gamma_M} \cdot \eta_i$$

The conversion factors η_i take into account the different influences on the value of resistance. Because the carrying and deformation behaviour of a bondline is significantly affected by the environmental temperature and the bondline thickness, the conversion factors η_t and η_m are introduced to the presented models. It is possible to describe the bondline resistance as a function of the specific influence value, based on small scale specimen tests with various temperatures and bondline thicknesses. The results of these experiments are considered in relation to reference values, which are generated from tests at normal condition (e.g. Table 1). Figure 5 presents the results for the tests and the determined conversion factors at different temperatures for the MS polymer-based adhesive. A polymer specific behaviour, a reduction of the bondline strength with increasing temperature, can be observed. Due to the fact that the conversion factors are referred to a defined limit state and thereby to a required target reliability of Eurocode, the determination of these factors is based on the design values of the resistance (see figure 5).

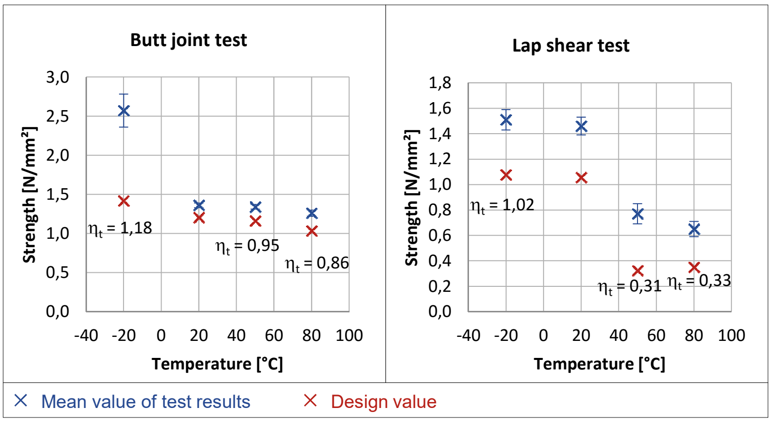


Figure 5: Conversion factors for a MS polymer adhesive

LONG-TERM BEHAVIOUR OF BONDED STEEL JOINTS

The presented investigations focused on quasi-static load situations and short-term loading. It is known, however, that the bondline strength can be reduced by long-term influences and cyclic loading. That is why ongoing research projects at the Chair aim at taking into account such effects.

Cyclic loading

The objective of an ongoing research project is to carry out cyclic test procedures for the application of the bonded façade connection, taking into account long-term effects (Pasternak *et al.* 2016). In a first step, representative load functions for the test sequences were deduced from actual measured wind speed and air temperature data from various weather stations. The main procedure of the project was presented at the Metnet Seminar 2015 (Ciupack *et al.* 2015).

In order to describe the general behaviour of bonded joints under cyclic loading, some investigations on small scale specimens and the façade connection were carried out under constant amplitudes. The stress ratio was chosen with a value of 0.1, which means a varying but permanent tensile loading for the bondline. To prevent heating of the adhesive due to mechanical load, the tests were carried out with a frequency of 5 Hz. If $2 \cdot 10^6$ load cycles are reached and no damage is detected, the value of the load is assigned within the fatigue strength. The results of these examinations for a polyurethane adhesive are shown in Figure 6.

All specimens failed with a cohesive failure of the bondline. The notch sensitivity (k) is calculated with a value of 6.19 for the butt joint tests and of 6.74 for the façade connection. The threshold of the load, which the joint can withstand permanently (fatigue limit S_k), is evaluated with a value of 3.3 kN for the small scale specimen and of 1.3 kN for the specimen component.

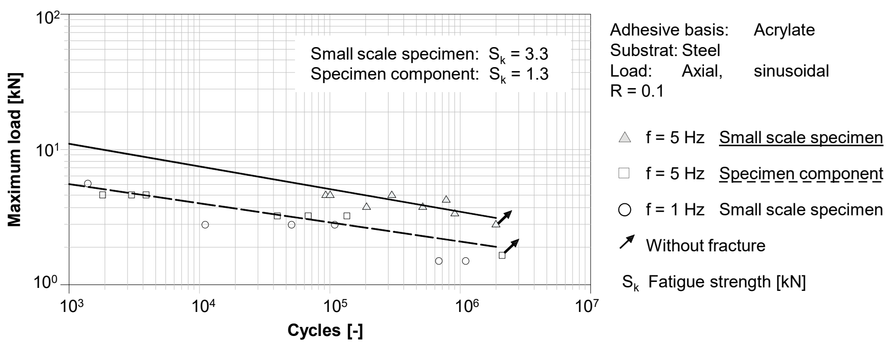


Figure 6: Comparison of test results of cyclic tests

Additional investigations showed a dependency of the bondline strength on the testing frequency (circular symbols in Figure 6) for small scale specimens. The lower the frequency, the smaller the fatigue limit strength. Based on these experiments it can be concluded that the real wind load sequences (low frequency and small amplitudes) mean higher fatigue damage than observed in the standard experiments. The future work of the Chair will focus on the possibilities of modelling the actual amplitude collective and frequencies as well as methods to reduce testing time of cyclic tests.

Creep behaviour

If the trapezoidal façade is used as structural or stabilizing construction element, the bonded connection is loaded by wind loads and dead loads simultaneously. Such long-term impacts lead to creep effects in the bondline. To study the general creep behaviour of bondlines, shear creep tests at overlapped steel plates bonded with a structural epoxy adhesive were carried out (Sahellie *et al.* 2015). The testing time totalled 110 days and the testing condition was air temperature of 20 °C ± 2 °C and relative humidity of 65% ± 4%. The objective was to estimate the bondline strength for a defined lifetime. Therefore, two model for viscoelastic materials were used, Findley's and Burger's models.

The test results showed that the shear creep behaviour is dependent on the magnitude of the applied stress. Moreover, it was found that Findley's model fits better to the data for shorter lifetime periods in general. However, it was found that longer lifetime of adhesives should be predicted by Burger's model. Findley's model, which indicated huge relative errors, is not useful for predicting long lifetimes due to the unlimited retardation spectrum of that model (Feng *et al.* 2005).

REINFORCEMENT OF STEEL STRUCTURE WITH BONDED CFRP LAMINATES

General investigation

An innovative alternative to typical reinforcement measurements of steel structure, e.g. welding or screwing of additional steel sheets, could be created by bonding of CFRP (carbon fibre reinforced polymer) laminates to the steel members. In the scope of an initial research project (Pasternak *et al.* 2015) applicability and efficiency of steel-CFRP-composites were studied. The main objectives were the testing based and analytical demonstration of the potential, as well as the development of recommendations for utilization of bonded CFRP reinforcements in steel structure.

Different influences of parameters, e.g. bondline thickness, joint length and surface pre-treatment of components being connected, were studied at double lap shear joints. Moreover, aging tests were performed on shear lap specimens, which were outsourced at various temperatures and climate conditions. The corrosion resistance was determined by means of salt spray tests.

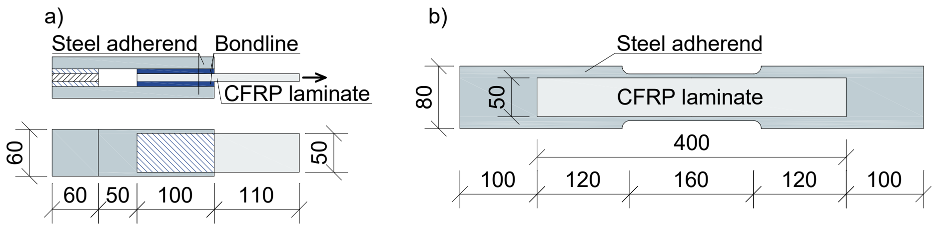


Figure 7: (a) Double steel-CFRP laminate-assemblies; (b) dumbbell specimen

These investigations were carried out using tensile shear tests on bonded double steel-CFRP laminate-assemblies based on DIN EN 1465 (see Figure 7a). It was shown that the carrying capacity of the specimens can be increased by increasing the joint length up to 100 mm. From this specific joint length, no essential improvement of bondline strength was possible. For all tests an adhesive failure at the laminates surface was observed, which can be explained by the characteristic of the employed adhesives, commonly used for the bonding of CFRP laminates to concrete. Thus, the adhesive is designed to have a lower strength than connected steel members. Taking into account the aging effects, the specimens were tested for climate change conditions based on DIN EN ISO 9142 with a single dependency (temperature) and double dependency (temperature and humidity). Depending on the kind of adhesive, degradation effects, but also post-curing effects, were observed.

The described experiments were repeated for 8 mm thick dumbbell specimens (see Figure 7b) loaded in tension. Supplementary to the mentioned influences, the arrangement of the CFRP reinforcement was investigated, single-sided and double-sided. Some results are presented in Figure 8. The efficiency of this reinforcing measurement is shown in the diagram, which shows that the resistance of the double reinforced specimen is 38% higher than that of the reference specimen.

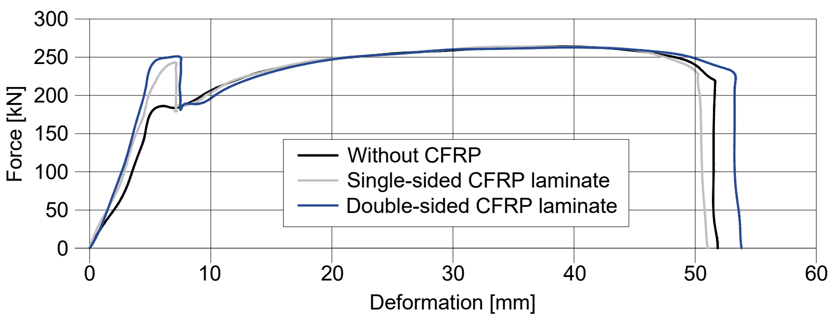


Figure 8: Diagram CFK

Refurbishment of steel members stressed by fatigue

An ongoing research project (Ummenhofer *et al.* 2016) deals with the refurbishment of steel structure with bonded CFRP laminates. The main idea is to substitute common refurbishment procedures, e.g. welded steel sheets, with this innovative rehabilitation method. Further, the possibility of refurbishment of cracked welds will be investigated. The efficiency of bonded CFRP laminates or sheets for the reduction and the avoidance of crack growth will also be studied. In this manner, different application dependent retrofitting techniques will be developed and cyclically loaded specimens will be tested. The focus is on long-term effects, e.g. the loss of pre-stress in CFRP sheets through the creep behaviour of a bondline. The development of a suitable testing methodology is planned for the characterizing of the strength and deformation behaviour of CFRP reinforced steel construction, aiming to establish this new refurbishment procedure.

CONCLUSIONS AND FUTURE WORK

Bonding technology is more than just an alternative joining method for steel structures, which can be shown by various applications and research projects in different fields. Despite many advantages of bonded joints, the civil engineering and especially steel construction community is reluctant to embrace this innovative technique. Often it is justified by doubts about the durability and a lack of experience. Interpreting such doubts as open questions and challenges creates the possibility and the potential for exceptional innovations. The general interest in developing standards as a basis for analysis and design of adhesive joints in steel is expected to rise with a growing number of functional and numerical applications.

The future work for the presented application examples for façade structures focuses on experimental investigations under variable amplitudes and the creation of a scientific based guideline for the design of bonded steel joints. For the introduction of alternative innovative bonded steel joints, the effort is limited to the development of engineering-models, planning and construction design. General technical approvals or individual approvals can be achieved more easily, thus sustainably increasing the innovative capacity of small and medium-sized enterprises.

REFERENCES

Dilger K., Pasternak H., et al. (2008), IGF Project No. 169 ZBG, Neue Konstruktionen durch Einsatz von Klebverbindungen im Stahlbau, Forschungsbericht für die Praxis P654, Forschungsvereinigung Stahlanwendung e. V., FOSTA, Verlags- und Vertriebsgesellschaft, Düsseldorf, Germany.

Meinz, J. (2010), Kleben im Stahlbau – Betrachtungen zum Trag- und Verformungsverhalten und zum Nachweis geklebter Trapezprofilanschlüsse und verstärkter Hohlprofile in Pfosten-Riegel-Fassaden, Dissertation, Brandenburgische Technische Universität Cottbus, Germany.

Pasternak H., Dilger K., et al. (2012), IGF Project No. 16494 BG, Entwicklung eines Eurocode-basierten Bemessungskonzepts für Klebverbindungen im Stahlbau (in Anlehnung an DIN 1990), Germany.

DIN EN 15870 (2009), Adhesives – Determination of tensile strength of butt joints, German version EN 15870:2009.

DIN EN 14869 (2004), Structural adhesives - Determination of shear behaviour of structural bonds - Part 2: Thick adherends shear test; German version EN 14869-2:2004.

DIN EN 1990 (2010), Eurocode 0: Basis of structural design; German version EN 1990:2002 + A1:2005 + A1:2005/AC:2010.

Pasternak H., Dilger K., et al. (2016), IGF Project No. 18161 BG, Untersuchungen zum Tragverhalten und der Lebensdauer von Klebverbindungen im Stahlbau unter zyklischer Belastung, ongoing research project, Germany, 01.04.2014 – 31.12.2016.

Ciupack Y. et al. (2015), Adhesive bonded steel structures under cyclic loading, Virdi, K.; Tenhunen, L. (Editors), Proceedings of the METNET Seminar 2015 Budapest, Häme University of Applied Science, 2015.

Sahellie S., Pasternak, H. (2015), Expectancy of the lifetime of bonded steel joints due to long-term shear loading, Archives of civil and mechanical engineering 15, pp. 1061 – 1069.

Feng C.-W., Keong C.-W., Hsueh Y.-P., Wang Y.-Y., Sue, H.-J. (2005), Modeling of long-term creep behavior of structural epoxy adhesives, International Journal of Adhesion & Adhesives 25, pp. 427 – 436.

Pasternak H., Feldmann M., Ummenhofer Th. et al. (2015), IGF Project No. 17700BG, Systematische Untersuchungen zur Verstärkung von Stahlkonstruktionen mit kohlefaserverstärkten Kunststoffen (CFK) - STAKOK, DVS, Germany.

DIN EN 1465 (2009), Adhesives - Determination of tensile lap-shear strength of bonded assemblies; German version EN 1465:2009.

DIN EN ISO 9142 (2004), Adhesives - Guide to the selection of standard laboratory ageing conditions for testing bonded joints; German version EN ISO 9142:2003.

Ummenhofer Th., Pasternak H., Feldmann M. (2016), IGF Project No. 19032 BG, Einsatz von geklebten Kohlestoff-Faserverbundwerkstoffen zur Sanierung ermüdungsgeschädigter Stahlkonstruktionen (FASS), ongoing research project, Germany, 01.02.2016 – 31.07.2018.

RESEARCH OF ULTRA-HIGH-STRENGTH AND WEAR-RESISTANT STEELS USING ADVANCED TECHNIQUES

Raimo Ruoppa, Kimmo Keltamäki, Rauno Toppila
Lapland University of Applied Sciences, Finland

Vili Kesti
SSAB, Finland

ABSTRACT

The usability of ultra-high-strength and wear-resistant steels has been researched for several years at Lapland University of Applied Sciences. Bendability tests have been carried out by using a commercial press brake and, recently, a new “ultimate bending machine” was built up to allow steels with higher strength and thickness to be tested. Research techniques have been developed in cooperation with SSAB and the University of Oulu. The techniques, as well as ultra-high-strength and wear-resistant steels, are reviewed in this paper.

Welding and wearing have also been researched for many years in cooperation with SSAB. The most common welding technique is mechanized MIG/MAG welding in method tests but shielded metal arc welding is also used for repair welding research. The quality and mechanical properties of welds are assessed using destructive testing results.

Wear-resistance tests are specialized field tests conducted under real-life conditions in the Outokumpu Chrome Oy Kemi mine, performed in cooperation with Tapojärvi Oy. The usual test targets of the wear-resistant steels are cutting edges and feed hopper plates. The wear of the wear-resistant plates was measured with the ATOS optical measurement system from GOM GMBH at Lapland University of Applied Sciences.

INTRODUCTION

Lapland University of Applied Sciences has an “Arctic Steel and Mining” (ASM) research team. The main focus of its work has been in the usability of ultra-high-strength and wear-resistant steels, as well as stainless steels. The team has participated together with the University of Oulu, SSAB Europe, and some other organizations in a research cluster which has recently published various papers at conferences and in journals. This paper mainly focuses on reviewing the techniques which have been utilized within these projects, as well as the introduction of ultra-high-strength steels. Detailed results of the projects can be read in the papers listed in the references below.

ULTRA-HIGH-STRENGTH AND WEAR-RESISTANT STEELS

Ultra-high-strength steels (UHSS) are usually considered to be steels with a yield strength of more than 550 N/mm2 and an ultimate tensile strength of more than 700 N/mm2. That is at least about 1.5 – 2.5 times higher compared to regular structural steels. Ultra-high-strength steels are suitable for fabrication but their higher strength and lower ductility make their processing more challenging and it becomes essential to follow instructions carefully. The high strength of UHS steels can be utilized in lightweight structures, which influences the costs and increases the lifetime of the devices. They are suitable for applications where, for example, weight is critical. Reducing the weight also reduces the consumption of steel, which also influences the carbon dioxide emissions during the production of the steel. Typical applications of UHS steels are, for example, the booms and frames of cranes, the frames of trucks and their beds, and parts of cages; see Figure 1.

Figure 1. Typical applications of UHS steels [SSAB]

Wear-resistant steels are typically used in applications such as the scoops and lip plates of earth movers, mining machines, the parts of the cement mixer trucks and batching plants that are subject to wear, agricultural and wood-handling machinery, bed structures, feeders and funnels, and the edges of different crushers; see Figure 2.

Figure 2. Typical applications of wear resistant steels [SSAB]

In the example shown below a demonstration is provided by means of a life-cycle approach of how a change from standard steel to UHSS in vehicles reduces carbon dioxide emissions. If, for example, 1.3 million tons of standard steel is replaced with one million tons of UHS steel in the production of cars:

1. when upgrading to a high-strength steel, the application retains its performance even though less steel is used. This results in weight savings for the steel application and means that less steel needs to be produced. Additionally, fewer resources are needed;
2. as much as 90% of the reduced environmental impact can be related to the use phase of lighter vehicles, through reduced fuel consumption;
3. from a life-cycle perspective, this case shows the substantial savings that can be achieved through using high-strength steels.

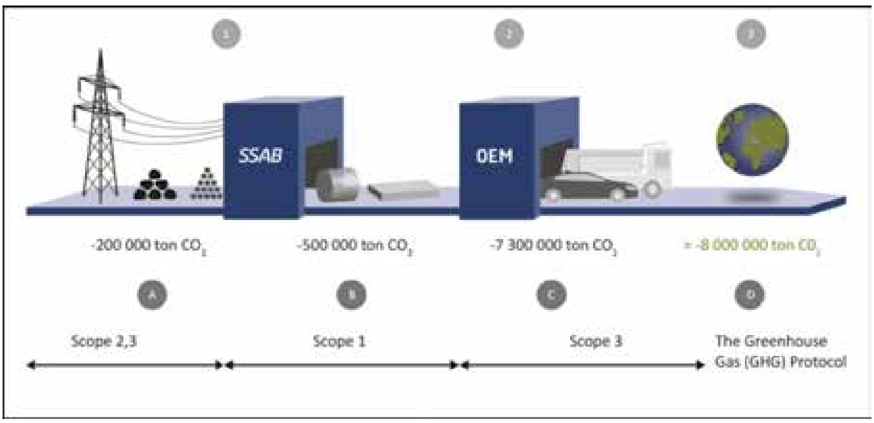


Figure 3. Example of the reduction of the carbon dioxide emissions through the use of UHS steels [SSAB]

A. When 300,000 tonnes less steel needs to be produced, the CO_2 emissions from upstream suppliers will decrease by 200,000 tonnes since less energy and raw material are needed.

B. The reduction in steel produced by 300,000 tonnes results in 500,000 tonnes fewer CO_2 emissions from SSAB's steel production.

C. When the current European vehicle fleet is upgraded, CO_2 emissions will decrease by 7.3m tonnes.

D. The total CO_2 savings arising from this hypothetical case are around 8m tonnes.

BENDABILITY

Manufacturing components for UHS steel applications almost invariably require bending, which is the most used, the best, and in many cases the only choice for forming, especially when the thickness of the sheet is increased. In modern high-strength steel structures (for example new generation boom and bed structures), bending is increasingly used and it often replaces, for example, welding. This leads in many cases to better fatigue durability of the structure at the same time as a reduction of the production costs.

Increasing the strength, however, makes bending more challenging and it becomes very important to obtain information about bendability and the factors which have an influence on the process. While the aim is to have a process that is as efficient and trouble-free as possible, following the instructions must be emphasized. That makes it very important to perform full-scale bendability tests which are carried out with real bending machines and samples large enough to correspond to actual parts. On the basis of the tests, correct instructions can be provided to customers.

In the bending, a steel plate is bent with, for example, a hydraulic press brake using a toolset containing a punch and die. The process, usually considered as three-point bending, is illustrated in Figure 4.

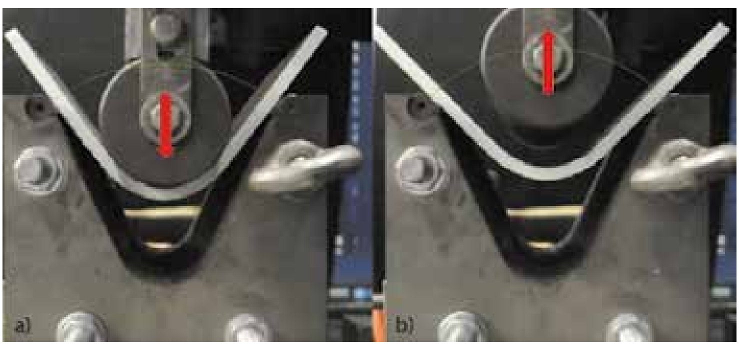


Figure 4. Bending of a steel plate in a V-die: a) punch in lower position; b) punch released

In Figure 4, spring-back may also be noticed. This phenomenon typically takes place in three-point bending. After the punch is released, the angle of the plate is increased as a result of the elastic deformation which is, in addition to plastic deformation, present in the steel. The spring-back may be measured using a video camera. Two images are sampled from the video, one from the lower end of the punch and another after the release of the punch; see Figures 4a and b. The spring-back angle is measured from the difference between the angles detected from the images. In general, greater the strength of the steel, the higher the spring-back, and knowledge of the magnitude of the spring-back is valuable for foundries manufacturing steel products.

When the strength of steel increase, its formability usually decrease. Figure 4 also illustrates the bending radius, which, in practice, corresponds to the radius of the punch. When the bending radius decreases, the strain on the outer surface increases and the probability of failure becomes higher. Therefore, the bending radius has to be large enough to avoid failures. In bendability tests, the minimum bending radius (Rmin) of the material, i.e. the smallest radius which is able to be used without failures, is usually defined. The result of the test is evaluated by means of visual inspection. Samples which have been bent using various bending radii are shown in Figure 5a – c. As a result, various degrees of failure have been developed on the surface. For the quality of the bend, certain requirements have been laid down and on the basis of these requirements, the result of the test will either be accepted or not.

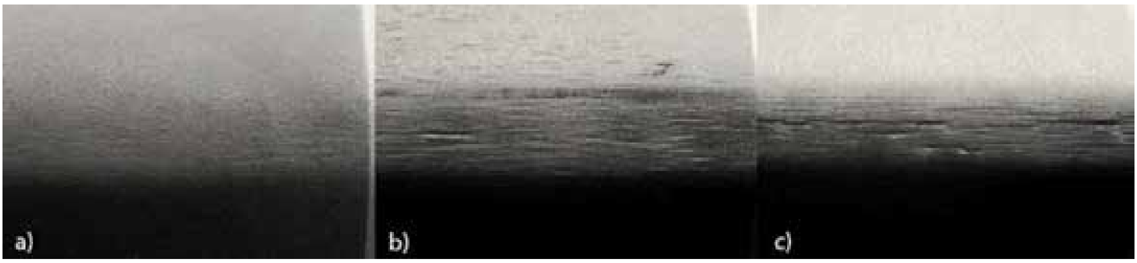


Figure 5. a) No failures; b) and c) failures appeared in the steel as a result of too small a bending radius

After the minimum bending radius has been reached, a sufficient number of repetitions is carried out using the accepted bending radius. Hence the durability of the material is able to be determined and the steel manufacturer is able to guarantee a minimum bending radius, for example, three times the thickness of the sheet (Rmin=3xt). The value usually depends on the grade and thickness of the steel and typically varies between 2 and 6 with UHS steels.

In addition to basic bendability testing, detailed investigations of the samples have also been carried out. With the GOM ARGUS 3D forming analysis system, samples have been studied with the aim of getting more detailed information about the metallurgical phenomena involved in bending [Arola et al. 2015, Ruoppa et al. 2014]. In this technique, a grid is marked on the surface of the sample before bending. On the basis of the change in the grid, a computer system calculates the strain distribution on the surface. The system is illustrated in Figure 6a and an example of a strain map is shown in Figure 6b. As a result, information about the processes during failure and the factors affecting them is gained, which helps the steel producer to develop products and customer instructions.

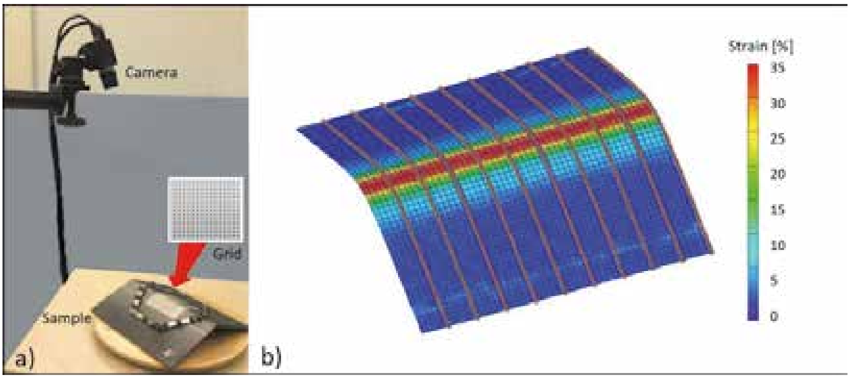


Figure 6. a) Measurement of the strain distribution with the GOM ARGUS 3D forming analysis system; b) example of strain mapping in bent sample

A more detailed study of the samples has also been performed by microscopic examinations. Figure 7 shows a microscopic image of the cross-section of a bend. From the image, scratches beneath the surface, as well as the reduction of the thickness, can be detected. Hardness may also be measured from the cross-section and by means of minimum hardness (red line); the neutral axis has been located in different cases [Kesti et al. 2014 & 2015]. The neutral axis refers to the line which represents zero deformation. By means of the neutral axis the so called k-factor, which is utilized in the design of products which are manufactured by bending, is defined. If the k-factor is known, material loss and the demand for after-treatment are reduced.

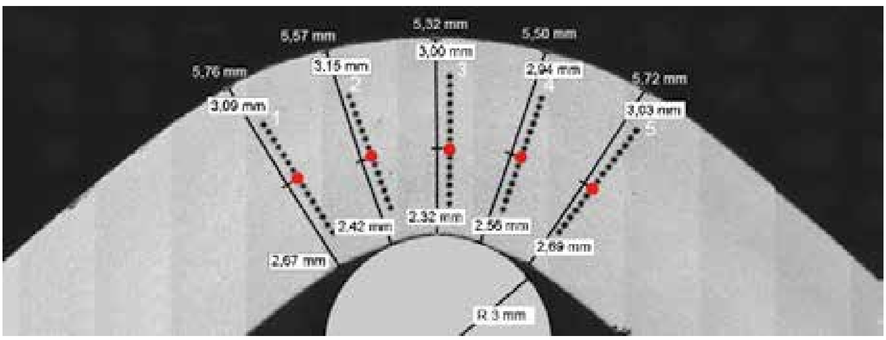


Figure 7. Microscopic image of the cross-section of the bend. The neutral axis is marked by red points based on the hardness measurements

Bending a steel plate by means of a hydraulic press needs a force with a magnitude that depends on the strength and dimensions of the material being bent, as well as the dimensions of the tools being used. When bending tests are carried out, the force is usually measured. On the basis of the measurements, models for the prediction of force have also been developed [Ruoppa et al. 2014] which may be utilized in planning product manufacturing. As the strength and thickness of the steels being tested are increasing all the time, the demand for stronger machines has been rising. Beside the regular 220-ton press brake which has been in use, an idea for a new "ultimate bending machine" was proposed [Toppila et al. 2011] and it was built as well.

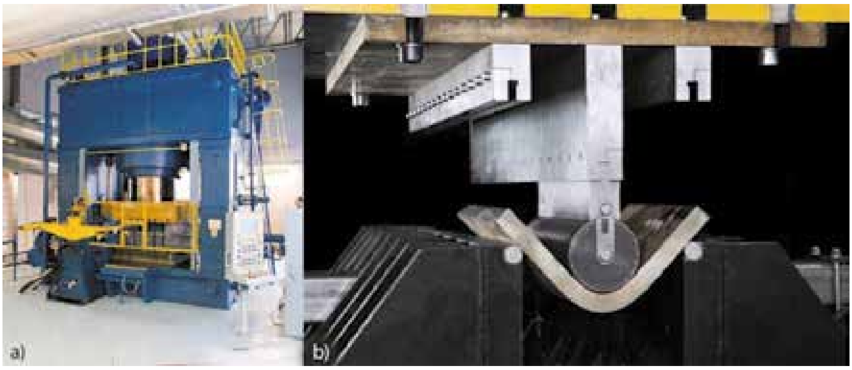


Figure 8. a) Hydroforming machine and b) bending tools built in the machine

Figure 8a shows a hydroforming machine which is located at the Tornio campus. The maximum force of the main cylinder is 3000 tons, which is adequate for heavy-duty bending. Using the machine for bending tests was planned in cooperation with SSAB and the special tools shown in Figure 8b were designed and constructed. From now on it will be possible to bend even 60-mm-thick UHS steel plates and the tests have already been started. The results have been encouraging and the research will be continued.

WELDING

The cooperation between Ruukki and Kemi-Tornio University of Applied Science (currently SSAB and Lapland University of Applied Sciences) within welding research has continued for several years. The first research projects were focused on different cutting methods, welding wires, UHS and welding, and the repair welding of wear-resistant steels. Advanced techniques were used for the investigation of the quality and mechanical properties of the welds.

In the majority of the welding tests, the SFS-EN ISO 15614-1 standard is applied. This standard "Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys" includes all the tests which are necessary for ascertaining the quality and mechanical properties of the welds. The most common investigation cases reported are pWPS (Preliminary Welding Procedure Specification) but in some cases an official qualification to WPS (Welding Procedure Specification) has also been carried out. In order to ensure the reliability of the test results, the ASM (Arctic Steel and Mining) R&D group follows the SFS-EN ISO/IEC 17025 laboratory standard "General requirements for the competence of testing and calibration laboratories". Some of the investigation techniques being that are used are shown in Figure 9.

Figure 9. Tensile test, impact test, and hardness test

Lapland University of Applied Sciences has also worked in cooperation with the Czech Technical University in Prague. The first research project was focused on the use and evaluation of advanced techniques for the investigation of the behaviour of high-strength steel. The techniques presented included optical strain measurement in tensile tests, a crack propagation study, and the idea of using a hydroforming machine for bending tests. Welded connections of common-grade steels have been investigated and verified for several years; detailed rules for both the welding technology process and structural engineering design are therefore clearly given in design standards and other prescriptions. On the other hand, new or improved steel processing techniques allow structural steel grades with a tensile strength exceeding 1300 MPa to be produced. The main reason why new high-strength steels cannot be used in the engineering praxis is a lack of knowledge about the behaviour of such steels in structures. These characteristics are controlled not only by the mechanical properties of the base material but also with regard to the technological process and its procedures and quantities, such as, for instance, heat input, grade, the diameter and type of welding consumable used, the welding method, number of passes (single or multilayer welds), preheating level, cooling rate, geometry of the weld, and others. [Sefcikova et al. 2015].

Research into Arctic welding has been developed within the TEKES project WELDARC 2015 – 2017 (*Improvement of productivity and quality of welding on special steels in Arctic conditions*). The aim of this project is to reach a new level of know-how related to Arctic welding and to develop collaboration between steel producers and downstream enterprises in Lapland as well as research and educational institutes. The eco-efficiency of the welding of ultra-high-strength and wear-resistant steels is developed; the occupational safety of operations is enhanced by developing more precise control for those steels that are susceptible to cold cracking; the monitoring of the conditions of the welding is built up (Figure 10); the enterprise networking and problem-solving capability for the Arctic welding are improved; these are a few examples of the practical applications developed from the project results [Keltamäki 2016].

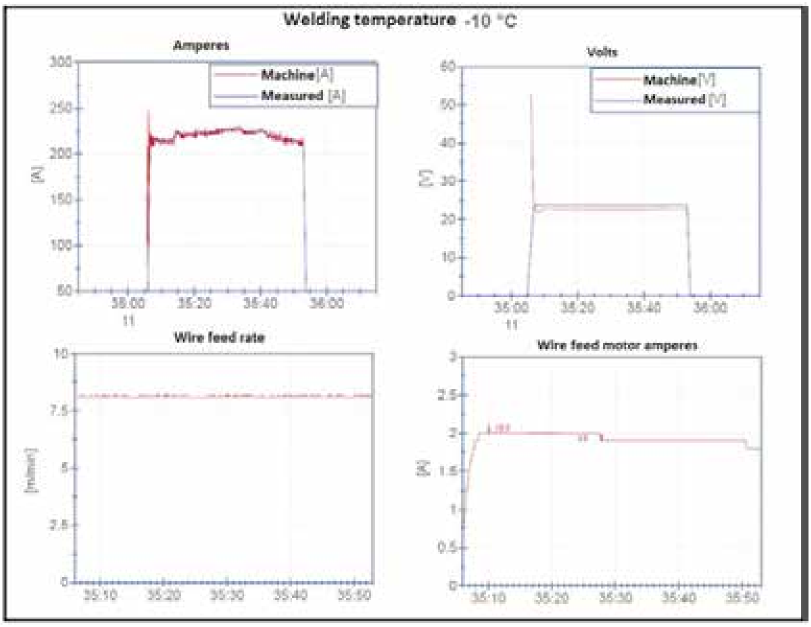


Figure 10. Monitoring of welding conditions (Rovaniemi Arctic Power laboratory)

WEARING

Wearing has also been under research for several years at Lapland University of Applied Sciences. The best places to evaluate wearing conditions are in mines. Finnish mines such as Kittilä, Sodankylä, and Kemi have many targets for wearing research. The Outokumpu Kemi mine, being the nearest one to the ASM R&D group, is the most commonly used one, and conditions in that mine are also the hardest when considering wearing. Therefore, it is possible to compare real-life and laboratory tests. Many application-oriented laboratory wear test devices for such purposes have been developed by the Tampere Wear Center located in southern Finland.

Field tests of the cutting edge of a loading machine and the wear plates of a feed hopper were carried out with the aim of evaluating the application-oriented test methods and to get more detailed information for the numerical modelling of the wear. The plates were constructed using the special wear-resistant steels Raex and Hardox. The wearing of the side plates was measured with the ATOS optical measurement system from GOM GMBH at Lapland University of Applied Sciences. The plates were measured using ATOS before assembly and after wearing. Some ATOS measurements are shown in Figures 11 and 12. The weights of the plates were also measured before and after wearing and so it was possible to report the total material loss exactly. Hardness tests and microscopic analysis are also included in the normal procedure.

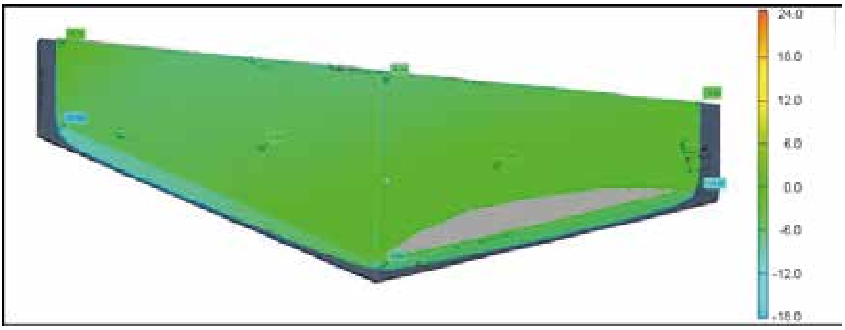


Figure 11. Wearing of cutting edge

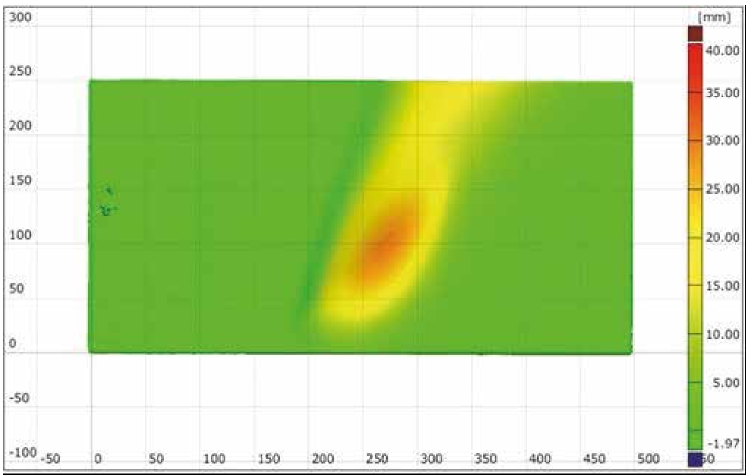


Figure 12. Wearing of side plate

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of Meripohjola-Hanke and TEKES – the Finnish Funding Agency for Technology and Innovation – for their support for the METNET Network.

REFERENCES

Arola, A-M., Kesti, V., Ruoppa, R. (2015). The Effect of Punch Radius on the Deformation of Ultra-High Strength Steel in Bending. Proceedings of the 16th International Conference on Sheet Metal, pp 139 – 146, Erlangen, Germany, 16 – 18 March, 2015.

Joutsenvaara, J. (2013). Forming limit curve of high strength steel with the help of digital image correlation. Proceedings of the METNET Seminar 2013, Luleå, Sweden, 22 – 23 October 2013.

Joutsenvaara, J. (2012). Investigation of strain localization of high strength steel with the help of digital image correlation. Proceedings of the METNET Seminar 2012, Izmir, Turkey, 10 – 11 October 2012, HAMK UAS, ISBN 975-951-784-592-2, pp.19 – 30.

Keltamäki, K. (2016). WELDARC, The Lapland University of Applied Sciences explores the improvement of productivity and quality of welding on special steels in Arctic conditions. Accepted for publishing in Pan European Networks: Science & Technology 20 September 2016.

Kesti, V., Kaijalainen, A.J., Mourujärvi, J., Ruoppa, R. (2015). Bendability and microstructure of Optim® 700 MC Plus. Nordic Steel Construction Conference, Tampere, Finland, 23 – 25 September 2015.

Kesti, V., Kaijalainen, A., Väisänen, A., Järvenpää, A., Määttä, A., Arola, A-M., Mäntyjärvi, K., Ruoppa, R. (2014). Bendability and microstructure of direct quenched Optim 960QC. Materials Science Forum, Trans Tech Publications, Switzerland Vols. 783 – 786, pp 818 – 824.

Ruoppa, R., Toppila, R., Kesti, V., Arola, A-M. (2014). Bendability tests for ultra-high-strength steels with optical strain analysis and prediction of bending force. Proceedings of the METNET Seminar 2014, Moscow, Russia, 21 – 22 October 2014, HAMK UAS, ISBN 975-951-784-693-6, pp. 68 – 78.

Ruoppa, R., Toppila, R., Sipola, J., Kesti, V. (2012), Bending properties of some ultra-high-strength steels. Proceedings of the METNET Seminar 2012, Izmir, Turkey, 10 – 11 October 2012. HAMK UAS, ISBN 975-951-784-592-2, pp.10 – 18.

Sefcikova, K., Brtnik, T., Dolejs, J., Keltamäki, K., Toppila, R. (2015). Mechanical Properties of Heat Affected Zone of High Strength Steels. IOP Conference Series: Material Science and Engineering. 2nd International Conference on Innovative Materials, Structures and Technologies, Riga Technical University in Riga, Latvia, 30 September-2 October 2015.

Siltanen, J., Kesti, V., Ruoppa, R. (2014). Longitudinal bendability of laser welded special steels in a butt joint configuration, Proceedings of International Congress on Applications of Lasers & Electro-Optics, October 19 – 23, 2014, San Diego, USA.

SSAB website (2016). URI: http://www.ssab.fi/ssab-konserni/kestava-kehi tys#!di=discover401DE95158784C5FA3329B8231ADD611, Cited 15 August 2016.

SSAB imagebank (2016). URI: http://imagebank.ssab.com/SSAB/#1480314741475_0, Cited 15 August 2016.

Toppila, R., Dolejs, J., Kauppi, T., Brtnik, T., Joutsenvaara, J., Vaara, P., Ruoppa, R. (2011). Investigation of behavior of HSS using advanced techniques. METNET Seminar 2011 Aarhus, Denmark, 12 – 13 October 2011. HAMK UAS, 978-951-784-556-4, pp 24 – 36.

STRENGTH OF CIRCULAR HOLLOW SECTION COLUMNS

Kuldeep S. Virdi
Emeritus Professor of Structural Engineering
Department of Civil Engineering
City, University of London, UK

INTRODUCTION

Circular Hollow Sections offer considerable benefits when used as compression members. The geometry of the section offers the maximum possible value of radius of gyration, resulting in superior performance against instability. As advances in materials technology result in higher grades of steel, it becomes imperative to reassess the instability behaviour of structural members made from higher grades of steel. Eurocode 3 (EN 1993-1-1:2003) permits the use of steel grades up to S460. Recent research has targeting use of circular hollow sections made of aluminium (Zhou and Young 2006) and further as concrete filled steel tubes (Han *et al.* 2007).

Although nonlinear finite element method can be used to determine the ultimate failure load of such columns, the modelling process takes considerable time and effort and for accurate modelling using solid elements often requires considerable computer time per run even on modern day computers. This paper describes a fast and yet accurate method for calculating the strength of eccentrically loaded circular hollow section columns. The method is based on the use of finite differences. A range of applications of the finite difference approach has previously been described by the author (Virdi 2006).

ADVANCED CALCULATION MODEL

The method of analysis presented here simulates the process of physically testing a slender column. A small axial load is applied and the deflected shape of the column is calculated. The load is then increased and the process repeated, until for a given applied load no equilibrium deflected shape is obtainable. The highest load, for which a deflected shape can be obtained, is taken as the failure load of column. An interpretation of this is that the stiffness of the column at the maximum applied load has vanished. Appropriate nonlinear stress-strain characteristics of steel are used. Initial imperfections in the form of lack of straightness can be specified. The method described here is for an axial load acting at an eccentricity.

STEEL STRESS-STRAIN CHARACTERISTICS

It is customary to idealise the stress-strain characteristic of steel as elastic plastic or a series of straight lines. Strain hardening can be considered by adopting an elastic-elastic bi-linear relationship, where the post-yield elastic modulus is adopted as a very small fraction (1/10000 or similar) of the Young's modulus of steel. Current version of Eurocode 3 (EN 1993-1-1:2003) permits the use of stress-strain characteristics obtained from tests when performing non-linear structural analysis.

STRUCTURAL MODEL

The analysis described in this paper is for eccentrically loaded concrete filled tubular columns. The column may have different eccentricity of loading at the two ends. The model is shown in Figure 1.

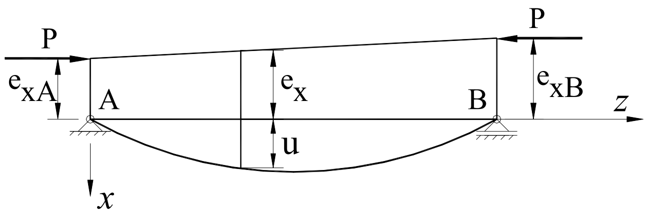


Figure 1 - Structural model

The cross-section is described by the outer radius R_o and the inner radius R_i as shown in Figure 2. The effective line of compression joins the two end eccentricity positions of the applied thrust. The governing equation of equilibrium at a point distance from the origin can be stated thus:

$$M = P(e_x + u) \quad (2)$$

where, at the point under consideration, $\boldsymbol{M}$ is the internal moment, $\boldsymbol{e_x}$ is the effective eccentricity, and $\boldsymbol{u}$ is the deflection .

Equation (2) can be re-written as:

$$u = M / P - e_x \quad (3)$$

Since equilibrium needs to be satisfied in the deflected state of the column, the internal stress-resultants depend upon the displacements, u . Hence, this equation may be written in symbolic form as:

$$u = U(u) \quad (4)$$

where U is a complex function, not easily expressed in a closed form.

A solution of the above equation requires calculation of internal stress resultants taking into account the column curvature, cross section shape and material stress-strain characteristics. This is achieved by establishing the moment-thrust-curvature relations. The solution also requires calculation of the deflected shape to be consistent with curvatures that cause the internal strains and stresses at all points along the length of the column.

MOMENT-THRUST-CURVATURE RELATIONS

The moment-thrust-curvature relations are a complex function due to the generality of the material stress-strain characteristics of steel. An analytical formulation is, in general, not feasible. Recourse is taken to numerical methods. It is assumed that upon flexure, a plane cross-section remains plane as shown in Figure 2. This results in the corollary that the strains vary linearly within the cross-section. The neutral axis may well be inside or outside the cross-section. The diagram also shows the stress-strain characteristics of steel relative to the neutral axis.

The two stress resultants can be expressed as:

$$P = \int_A \sigma \, dA \tag{5}$$

and

$$M = \int_A \sigma \, x \, dA \tag{6}$$

In the above equation, x has the origin at the centroid of the cross-section.

For purposes of evaluating the stress resultants numerically, the cross-section is divided into a number n of slices parallel to the neutral axis and the integrations are replaced by summations. The strain at a point within the cross-section is obtained by:

$$\varepsilon = \phi \, x \tag{7}$$

where, x is the distance of the point from the neutral axis and ϕ is the curvature at the cross-section. The depth of the neutral axis from the top of the cross-section is denoted by d_n .

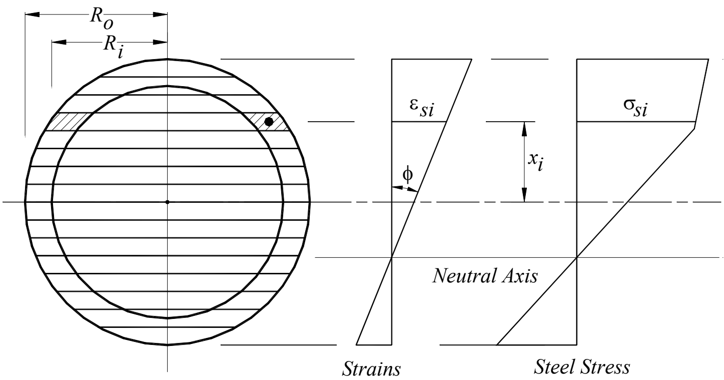


Figure 2 - Discretization of the cross-section for moment-thrust-curvature calculations

Equations (5) and (6) become:

$$P = \sum_{i=1}^{n} \sigma_{si} \, \Delta A_{si} \tag{8}$$

$$M = \sum_{i=1}^{n} \sigma_{si} \, \Delta A_{si} \, x_i \tag{9}$$

The stress σ_{si} is evaluated at the centre of the slice for steel, ΔA_{si} is the area of the steel zone within the slice, and x_i is the distance from the centroid to the mid-height of the slice.

Figure 3 shows an enlarged view of a typical slice, bounded between the lines 1-1 and 2-2.

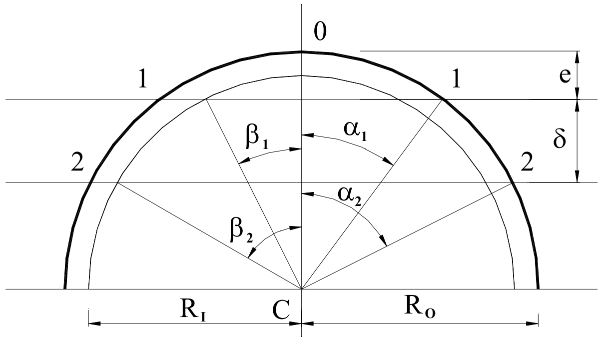


Figure 3 - View of inner and outer zones within a slice.

The angle α_1 can be obtained for a distance e from the top as follows:

$$\alpha_1 = \cos^{-1}\{(R_o - e) / R_o\} \tag{10}$$

Similar equations can be written for the other angles required for this strip. For example,

$$\beta_2 = \cos^{-1}\{(R_i - e - \delta) / R_i\} \tag{11}$$

The area of the whole slice between the lines 1-1 and 2-2 can be shown to be given by:

$$W = R_o^{\ 2}(\alpha_2 - \sin\alpha_2 \sin\alpha_2) - R_o^{\ 2}(\alpha_1 - \sin\alpha_1 \sin\alpha_1) \tag{12}$$

Likewise, the area of the hollow zone within the same slice can be obtained by replacing the radius R_o with R_i and using appropriate angles:

$$H = R_i^{\ 2}(\beta_2 - \sin\beta_2 \sin\beta_2) - R_i^{\ 2}(\beta_1 - \sin\beta_1 \sin\beta_1) \qquad 13)$$

The area of the steel zone within the slice is simply:

$$S = W - H \tag{14}$$

It would be appreciated that, using these equations, accurate evaluation of integrals in Equations (5) and (6) can be obtained very rapidly.

DETERMINATION OF THE POSITION OF NEUTRAL AXIS

The criterion used to establish the position of neutral axis at a given point is that the value of the force stress-resultant obtained from the above procedure should match the externally applied force at the ends of the column.

The procedure adopted here to calculate the depth of neutral axis $_n$ to the neutral axis is a variation of Newton's method of iteration using the equation:

$$d_{r+1} = d_r - P^{'}(d_r) / P(d_r) \tag{15}$$

where, d_r is a trial value of the depth of neutral axis for iteration r, $P(d_r)$ is the value of the stress resultant calculated for the current trial value of d_r, $P^{'}(d_r)$ is the current rate of change in $P(d_r)$, and d_{r+1} is the improved value of the depth of neutral axis from the current iteration. Except for the first trial, $P^{'}(d_r)$ can be obtained numerically from the current value of $P(d_r)$ and the value obtained in the previous iteration $P(d_{r-1})$. Experience indicates that the method converges extremely rapidly even when parts of the cross-section have significant non-linear stresses.

DETERMINATION OF EQUILIBRIUM DEFLECTED SHAPE

To determine the deflected shape of the column under an applied load, an influence coefficient method is used, based on finite difference formulae for curvatures. The column length is divided into a number of segments of equal step length, although it is also possible to formulate a solution based on unequal step size. Because of the speed with which a solution is obtained by this method, greater accuracy can be achieved simply by using a larger number of equal segments rather than trying to adaptively vary the step size.

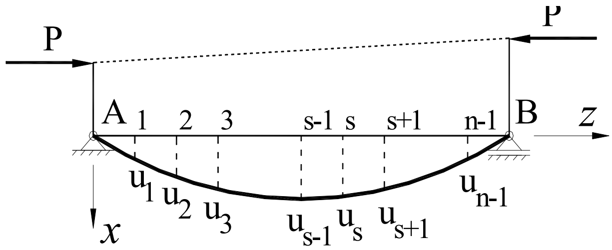


Figure 4 - Finite difference discretization of the column length

Writing Equation (4) for each of the unknown displacements, u_1, u_2, ... u_n, a set of simultaneous equations is obtained, represented below in symbolic form.

$$\{u\} = \{U(u)\} \tag{16}$$

Starting with an assumed vector $\{u\}_r$ at iteration number $\boldsymbol{r}$, an improved solution is given by:

$$\{u\}_{r+1} = \{u\}_r - [I-K]^{-1}(\{u\}_r - \{U\}_r) \tag{17}$$

In the equation above $[I]$ is the unit matrix and $[K]$ is a Jacobian matrix, defined by:

$$K_{ij} = \frac{\partial U_i}{\partial u_j} \tag{18}$$

In practice, when using the finite difference formulation, matrix $[K]$ is reduced to a tri-diagonal form, as explained below.

When limiting the analysis to small displacements, curvature is approximated by the second derivative. In finite difference form, at point $\boldsymbol{s}$, the curvature is:

$$\phi_s = \frac{d^2u}{dz^2} = \frac{u_{s-1} - 2u_s + u_{s+1}}{h^2} \tag{19}$$

where, h is the step size along the column length. It can be shown easily that:

$$\frac{d\phi_s}{du_{s-1}} = \frac{d\phi_s}{du_{s+1}} = -\frac{1}{2}\frac{d\phi_s}{du_s} = \frac{1}{h^2} \tag{20}$$

Also, $$\frac{dU_s}{du_s} = \frac{dU_s}{d\phi_s}\frac{d\phi_s}{du_s} = \frac{dU_s}{d\phi_s}\left(-\frac{2}{h^2}\right) \tag{21}$$

Similarly, $$\frac{dU_s}{du_{s-1}} = \frac{dU_s}{d\phi_s}\frac{d\phi_s}{du_{s-1}} = \frac{dU_s}{d\phi_s}\frac{1}{h^2} \tag{22}$$

and, $$\frac{dU_s}{du_{s+1}} = \frac{dU_s}{d\phi_s}\frac{d\phi_s}{du_{s+1}} = \frac{dU_s}{d\phi_s}\frac{1}{h^2} \tag{23}$$

It follows that, $$\frac{dU_s}{du_{s-1}} = \frac{dU_s}{du_{s+1}} = -\frac{1}{2}\frac{dU_s}{du_s} \tag{24}$$

From Equation (19), it can be deduced that, for all t not equal to $s-1$, s or s:

$$\frac{d\phi_s}{du_t} = 0$$

This leads to the result that for all t not equal to $s-1$, s or $s+1$:

$$\frac{dU_s}{du_t} = 0$$

In other words, for each row in matrix $[K]$, there are only three non-zero terms centred over the diagonal. Obviously, in the first and last rows of the matrix, there will only be two, and not three, elements. Further, Equation (24) indicates that terms on either side of the diagonal have simple relationship with the diagonal terms. It should be noted that elements in one row do not have any simple relation with elements in any other row. Thus, the coefficient matrix generated by the above procedure is not symmetric.

To define the elements of the diagonal, at each point along the length, integrations have to be performed twice, once for the current value of the curvature, defined by Equation (19) and once by giving a small change to the deflection u_s, say of magnitude γ. The values of moment stress-resultant obtained in the two integrations lead respectively to the functions U_{s1} and U_{s2} giving approximately:

$$\frac{dU_s}{du_s} = \frac{U_{s2} - U_{s1}}{\gamma} \quad (25)$$

From this result, the other two non-zero elements in the row s of matrix $[K]$ can be defined using Equation (24). It would be appreciated that the above scheme represents a very efficient way of forming the nonlinear equations required for the solution.

DETERMINATION OF ULTIMATE LOAD

As stated earlier, the procedure for calculating the ultimate load commences with applying a small axial load and establishing the equilibrium deflected shape using the method described above. The applied load is then increased and the procedure is repeated, until an equilibrium shape is not obtainable in a pre-defined number of iterations. At this stage, the calculations can revert to the last solution obtained and reduce the increment in the load. In this manner, the ultimate load can be obtained for any desired level of accuracy.

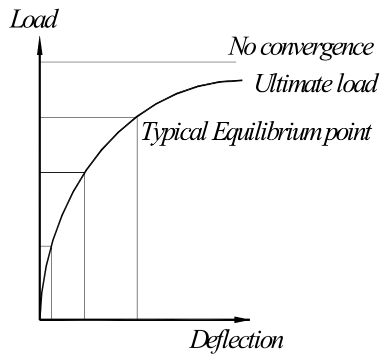


Figure 5 – Ultimate load calculation procedure

A computer program labelled TUBCOLS has been developed using the above method. To establish the validity of the method, comparisons with tests reported in literature are now described.

COMPARISON WITH TESTS REPORTED BY GANG SHI *ET AL.*

Gang Shi *et al.* (2014) conducted tests on 24 circular hollow section columns. The columns were loaded with equal eccentricity at both ends. The observations included lateral deflections. Key parameters of the columns are given in Table 1.

It should be pointed out that the length given is the distance between centres of rotation as listed for each test specimen in Ref [5]. The eccentricity values listed were stated to be derived from the longitudinal strain values measured around the periphery of the column which were converted to an applied bending moment, which divided by the axial load was adopted as the eccentricity.

Table 1 - Common properties

Test Specimen	Outer Diameter Mm	Tube Thickness mm	Effective Length mm	Out of Straightness mm	Loading Eccentricity mm
D420-20-1	274	6.01	2362	-0.60	10.20
D420-20-2	275	6.01	2361	-0.40	-2.77
D420-20-3	274	5.87	2362	0.60	2.71
D420-30-1	273	5.85	3305	-0.30	1.84
D420-30-2	273	5.95	3307	-0.75	-2.75
D420-30-3	273	5.91	3306	-2.25	11.72
D420-40-1	275	5.89	4248	1.60	5.88
D420-40-2	276	5.83	4249	0.85	-3.98
D420-40-3	271	5.91	4248	-1.05	6.57
D420-50-1	274	5.87	5193	2.95	0.10
D420-50-2	273	5.88	5192	-1.10	7.90
D420-50-3	273	5.88	5193	-0.20	2.85
D420-60-1	273	5.85	6134	0.40	-1.33
D420-60-2	273	5.95	6136	0.80	2.02
D420-60-3	272	5.91	6137	1.20	1.44
D420-20-4	274	6.01	2362	0.70	-29.33
D420-20-5	274	6.01	2362	1.00	6.79
D420-20-6	274	5.87	2362	-2.50	13.56
D420-40-4	273	5.94	4248	1.15	2.26
D420-40-5	276	6.11	4249	0.25	1.47
D420-40-6	269	6.15	4248	-1.20	0.15
D420-60-4	272	5.99	6134	0.55	4.30
D420-60-5	275	6.00	6134	-0.75	-2.55
D420-60-6	272	5.81	6135	-1.75	2.95

In the calculations presented here, steel is assigned a multi-linear stress strain characteristic shown in Figure 6 is used, using the experimentally recorded parameters reported in (Gang Shi *et al.* 2014). These are listed below in Table 2.

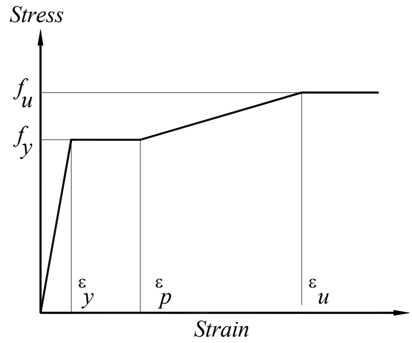


Figure 6 – Idealised stress-strain characteristic

Table 2 – Material Properties

	f_y MPa	f_u MPa	ε_y	ε_p	ε_u
D420-20-1	438	564	2179	21195	151329
D420-20-2	438	564	2179	21195	151329
D420-20-3	449	588	2269	20574	146414
D420-30-1	450	571	2321	24600	145107
D420-30-2	457	576	2406	24735	153722
D420-30-3	451	575	2336	24642	141022
D420-40-1	445	564	2202	25782	155329
D420-40-2	464	586	2273	22078	152648
D420-40-3	450	570	2305	25568	141368
D420-50-1	450	571	2321	24600	145107
D420-50-2	477	577	2387	26743	144093
D420-50-3	477	577	2387	26743	144093
D420-60-1	450	571	2321	24600	145107
D420-60-2	457	576	2406	24735	153722
D420-60-3	451	575	2336	24642	141022
D420-20-4	473	561	2440	33155	127424
D420-20-5	473	561	2440	33155	127424
D420-20-6	473	561	2440	33155	127424
D420-40-4	475	561	2400	37378	135251
D420-40-5	475	563	2526	30690	127424
D420-40-6	469	558	2393	31398	119578
D420-60-4	473	561	2440	33155	127424
D420-60-5	473	561	2440	33155	127424
D420-60-6	473	561	2440	33155	127424

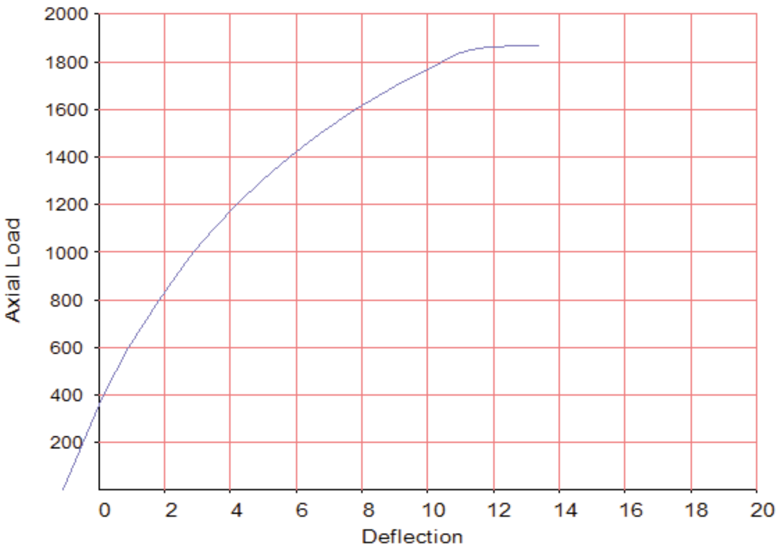


Figure 7 – Load deflection plot for column D420-50-2

Figure 7 shows a typical plot of applied load and calculated deflections, in this case for Specimen D420-20-1. The reducing stiffness of the column can be readily visualised, giving confidence in the calculated value of the ultimate load.

Table 3 lists the computed and test failure loads and their ratio. The mean value of the ratio obtained is 0.940 with a standard deviation of 7.4%. Clearly, for this set, the correlation between the test and computed failure loads is good and is on the conservative side.

Table 3 - Comparison between computed and test failure loads

Column	Test Strength, P_t kN	Computed Strength, P_c kN	Ratio P_c / P_t
D420-20-1	2090	1973.3	0.944
D420-20-2	2173	2137.8	0.984
D420-20-3	2178	2129.0	0.978
D420-30-1	2075	2147.9	1.035
D420-30-2	2075	2148.4	1.035
D420-30-3	2094	1918.4	0.916
D420-40-1	2027	1904.9	0.940
D420-40-2	2100	2126.7	1.013

D420-40-3	2026	1941.4	0.958
D420-50-1	2038	1997.2	0.980
D420-50-2	1997	1866.4	0.935
D420-50-3	2012	2090.2	1.039
D420-60-1	1957	1924.6	0.983
D420-60-2	1974	1800.9	0.912
D420-60-3	1960	1795.4	0.916
D420-20-4	2033	1761.1	0.866
D420-20-5	2375	2172.0	0.915
D420-20-6	2100	2042.1	0.972
D420-40-4	2356	2177.9	0.924
D420-40-5	2449	2347.7	0.959
D420-40-6	2306	2319.3	1.006
D420-60-4	2277	1762.7	0.774
D420-60-5	2329	1862.8	0.800
D420-60-6	2285	1762.9	0.772
		Mean	0.940
		Standard Deviation	0.074

Gang Shi *et al.* (2014) calculated the strength of their test columns using the finite element method. They obtained a mean value of 0.96 with a standard deviation of 5.98%. They commented that last three columns were made of galvanised steel which gave much higher test results compared with the calculated values based on the measured material properties. They attributed this to the fact that these columns were galvanised. The galvanisation process appears to have modified the material properties.

Ignoring the three results, the mean value of the ratio between the calculated load and the experimental failure load was found to be 0.962. The standard deviation of the 21 results is 4.62%. These numbers may be considered excellent correlation with experiments.

The numerical results presented here, based on the finite element method give accuracy which compares very well against the finite element method.

CONCLUSION

The paper describes a method for the ultimate load calculation of columns made of circular hollow sections. The method, based on the finite difference method is shown to give good results when compared with 24 tests reported by Gang Shi *et al.* (2014). The overall accuracy of the method is very similar to that obtained by the finite element method. The method presented here requires just a few lines of input to define the geometry, material properties, imperfections and loading, making it suitable for large scale parametric studies.

REFERENCES

EN 1993-1-1 (2003). CEN. Eurocode 3 - Design of steel structures - Part 1-1: General rules and rules for buildings. EN 1993-1-1:2003. European Committee for Standardisation, Brussels.

Zhou J-H and Young B (2006). Aluminium alloy circular hollow section beam-columns. Thin-Walled Structures, 44, 131–140.

Han L-H, Yao G-H and Tao Z (2007). Behavior of concrete-filled steel tubular members subjected to combined loading. Thin-Walled Structures, 45, 600–619.

Virdi K S (2006). Finite difference method for nonlinear analysis of structures. Journal of Constructional Steel Research, 62, 1210–1218.

Shi G, Jiang X, Zhou W, Chan T-M and Zhang Y (2014). Experimental study on column buckling of 420 MPa high strength steel welded circular tubes. Journal of Constructional Steel Research, 100, 71–81.

THE FLAT DOUBLE-LAYER GRID-CABLE STEEL-CONCRETE COMPOSITE STRUCTURE

G.M. Gasii
Ph.D., Associate Professor
Poltava National Technical Yuri Kondratyuk University, Poltava, Ukraine
Faculty of Civil Engineering
Department of Structures from a Metal, Wood and Plastics

ABSTRACT

The paper studies constructive concept of the flat double-layer grid-cable steel-concrete composite structure. The flat double-layer grid-cable steel-concrete composite structure is the new kind of roof system for long-span buildings. The composite structure has been developed in Poltava National Technical Yuri Kondratyuk University on department of structures from metal, wood and plastics.

The feature of the constructive concept is in the bottom chord that consists of flexible bars and top chord that is made from a concrete slab. The flexible bars are made from segments of steel cables that have special details at the ends through which the segments are connected to each other.

The bottom chord is not complex and its manufacturing and assembly does not take much time. Due to the use of steel cables, the total weight of the structure decreases, saving materials and, as a result, the total cost of construction also decreases.

The paper describes the results of the numerical investigation of load bearing capacity of a modular steel-concrete composite spatial unit.

INTRODUCTION AND PROBLEM STATEMENT

In the current development of scientific and technological achievements and increasing social needs of the population, there is a need to find more effective structural systems, including roof systems. The main requirements that apply to the structural systems of buildings, in addition to reliability and load capacity, is an architectural expression, aesthetics, ergonomics and good indicators of energy efficiency. The important aspect of designing and finding a constructive concept for new designs is the use of reliable and advanced materials. Steel and concrete with various modern fillings belong to the materials that satisfy these requirements.

The effectiveness of the developed designs also depend on how materials are used and on the behavior of constructions. It means that materials should be under appropriate forces, which they are resisting well for example steel is used in tension or compression elements but concrete is used as compressed elements. Considering this fact, it has been decided to combine steel bars and concrete slabs in a unified spatial design and further its research to a broad implementation in practice of construction. This is a promising direction of development of building structures.

ANALYSIS OF RECENT SOURCES OF RESEARCH AND PUBLICATIONS

The analysis has showed that traditionally the most known large-span spatial designs are made entirely of steel members, including flat double-layer grid [1]. However, there are examples of steel combined systems [2]. In addition, steel-concrete composite constructions are used widely in a variety of designs [3, 4]. These constructions are used in many sectors of industrial and civil construction [5]. Steel-concrete composite constructions are used as roof systems, slab system, columns, different plate structures and bearing elements of buildings and structures [6].

HIGHLIGHT UNSOLVED PARTS OF THE GENERAL PROBLEM

Based on the analysis of previous studies and taking into account the advantages steel-concrete composite constructions the issue of development of the structural concept of the new spatial structure systems with its use has not been fully investigated.

PROBLEM FORMULATION

The aim of the study is to identify the most promising and effective designs using the theoretical studies of the current state of construction and spatial steel and concrete composite structures. Given the physical and mechanical properties of materials and properties of structural elements is to offer and develop the new type of space structure systems.

THE MAIN MATERIAL AND RESULTS

The development of the construction industry is accompanied by the introduction of effective materials. The use of these materials allows structure systems with the necessary strength characteristics and technical-economic indicators, but together with their development there is a need for the development of new geometric shapes and structural concept.

Grid systems are the best known among long span and spatial structures. These systems have a great ability and flexibility to the form finding that is evidenced by many original shapes in the world [7].

Flat double-layer grids are allocated more frequently from the general class of the grid systems than others. That is why, for the development of the new type of space structure systems has been taken the flat double-layer grids as a basis. The original concept of structural system has been developed using world experience of shaping large-span constructions. This is about the flat double-layer grid-cable steel-concrete composite structure (Figure 1).

This is the new kind of a spatial construction, the essence of which lies in appropriate use of materials and their properties [8].

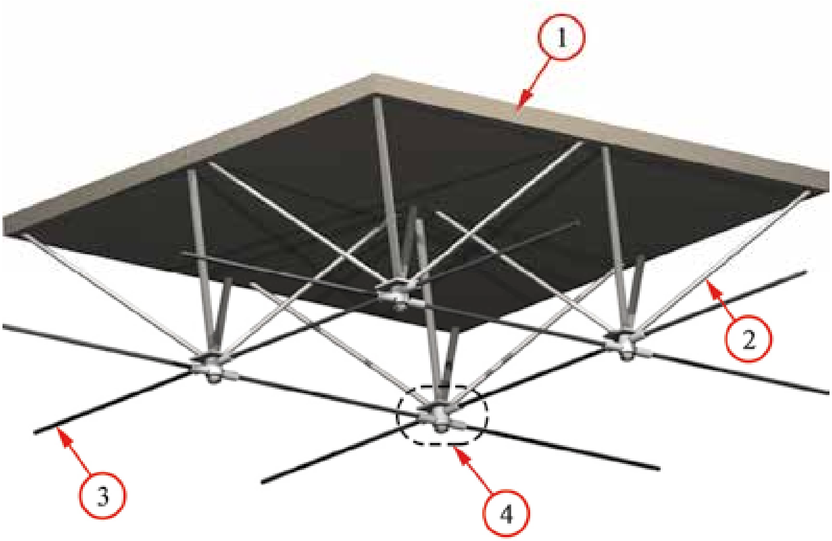


Figure 1. Segment of The flat double-layer grid-cable steel-concrete composite structure: 1 – a top chord; 2 – a diagonal; 3 – a bottom chord; 4 – a nodal bolted connections

The flat double-layer grid-cable steel-concrete composite structure consists of modular steel-concrete composite spatial units that are connected to each other through the nodal bolted connections (Figure 2) in a complete design.

Elements of construction are made with automated processes, especially this applies to the production of nodal parts and processing the ropes.

The modular steel-concrete composite spatial unit is made from segments of steel tubes and reinforced concrete slab.

The main feature of the reinforced concrete slab is the structural concept. Slab is made from cement-sand mortar and steel woven nets. The slab has a size of 1500×1500 mm in plan and depth of 60 mm. The slab is reinforced with woven steel nets and steel bars (Figure 3).

The nets for reinforcement are made from thin steel wire that had a diameter of 1.2 mm. The steel nets have a cell size of 20×20 mm. The distance between the woven steel nets is 5 mm. This distance is provided with steel disc-gaskets that were placed between nets. Steel disc-gaskets are placed at every 200 mm.

Steel nets and steel disc-gaskets are connected together with a cement-sand mortar in a single structure. This way of reinforcement of the slab allows reducing a weight and cost of materials in comparison with conventional reinforced concrete structures with the same bearing capacity [8].

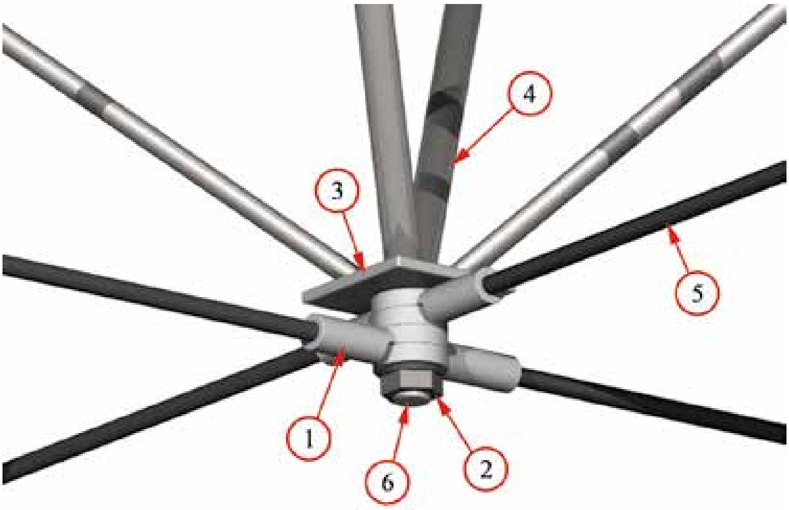


Figure 2. The nodal bolted connection: 1 – a connecting detail; 2 – a nut; 3 – a connecting plate; 4 – a diagonal; 5 – a bottom chord; 6 – a bolt

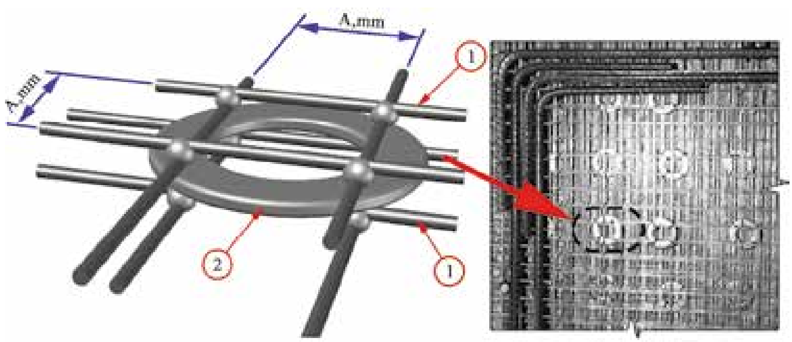


Figure 3. A Part of steel reinforcing mesh: 1 – a wire d=15 mm; 2 – a steel disc-gasket t=5 mm; A=25 mm

The average modulus of elasticity for different parts of the slab has been used for modeling its behavior.

Analysis of the stress-strain state of the construction has been investigated with the FE method. For this had been defined physical and mechanical properties of materials via experimental testing (Figure 4). The boundary conditions in the numerical modeling are shown in Figure 5. The von Mises stress contour shown in Figure 6 is the result of the solving of numerical model under the estimated load.

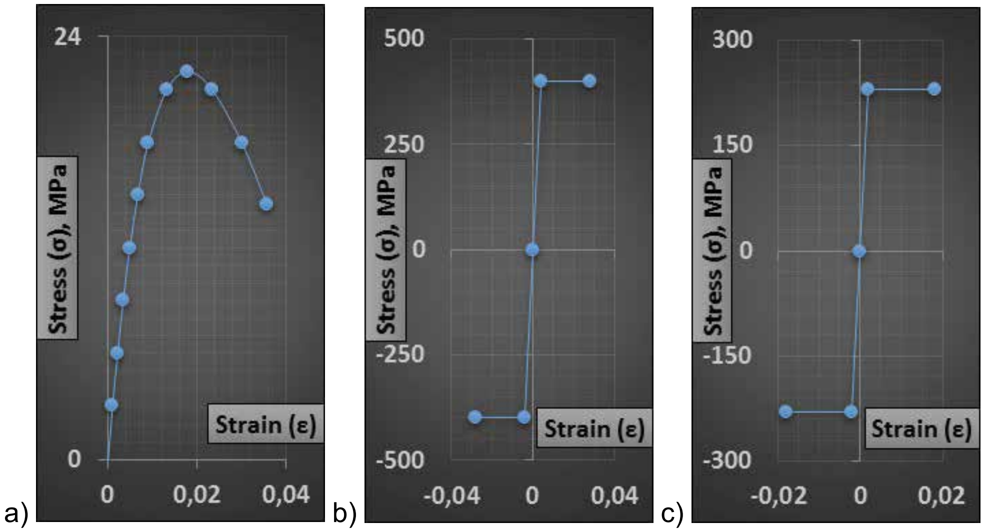


Figure 4. The stress-strain curve: a) of concrete; b) of steel reinforcement; c) of steel

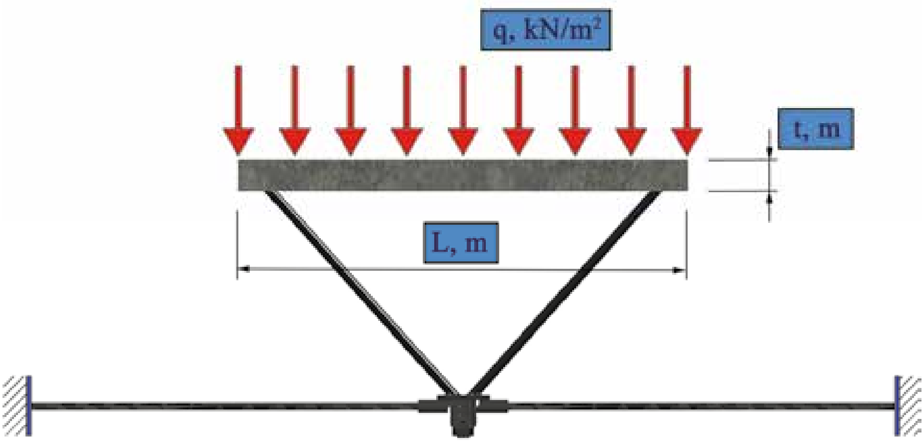


Figure 5. The boundary conditionals: L – the length, 1.5 m; t – the thing, 0.06 m; q – the uniformly distributed load that equals snow load for Ukraine

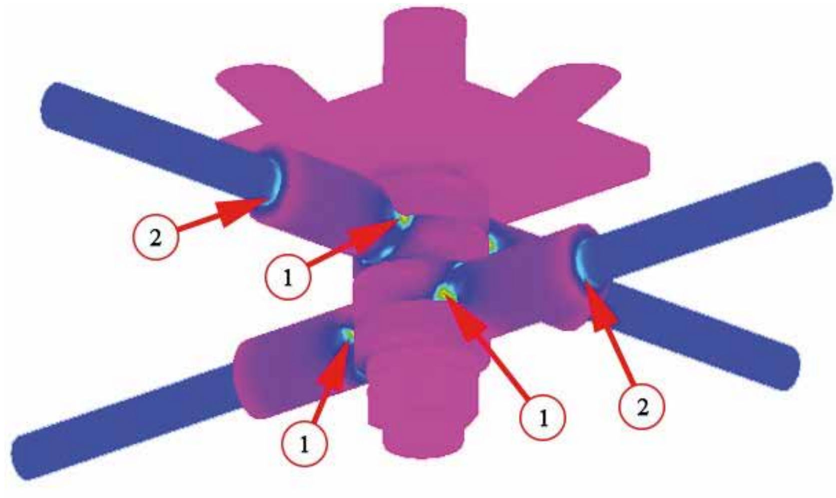


Figure 6. The von Mises stress contours: 1 – the region 1; 2 – the region 2

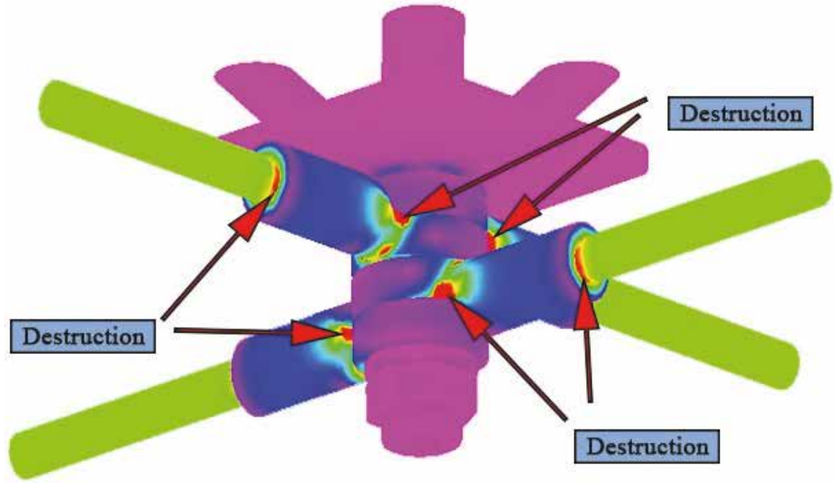


Figure 7. The von Mises stress contours at the destruction load

Figure 7 shows a failure (destruction) model of nodal connection of the developed construction. The contour of solid von Mises stresses (see Figure 6) shows that the maximum stress that has appeared is less than the limit stress of steel. The factor of safety of steel nodal details is 1.3. That makes it possible to optimize the shape of the steel details. The largest stresses are in the regions1 and 2.

The destruction of steel details (see Figure 2) came in the regions 1 and 2 when a load had exceeded the estimated load 1.3 times.

DISCUSSION AND CONCLUSIONS

The study deals with a new kind of spatial construction that consist of modular units.

From the numerical investigation is obtained the stress-strain state of the flexible bottom chord of the flat double-layer grid-cable steel-concrete composite structure. The von Mises stress contours have been obtained with FE method. The stress contours gave an opportunity to identify the locations of the maximum stresses and strains. The factor of safety was obtained using information about the maximum stress and strains.

Research confirms the effectiveness of structural concept of the construction.

REFERENCES

[1] Chilton J. Space grid structures. Boston: Architectural Press, 2007,180 p.

[2] Ivanyk I., Vybranets Y. and Ivanyk Y. Research of composite combined pre-stressed construction. Acta Scientiarum Polonorum, 2014. no. 13(2), pp. 81–88.

[3] Gasii G.M. Technological and design features of flat-rod elements with usage of composite reinforced concrete. Metallurgical and Mining Industry, 2014, no. 4, pp. 23–25.

[4] Стороженко Л.І. and Гасій Г.М. Нові композитні матеріали кріплення гірничої виробки. Науковий вісник Національного гірничого університету, 2015, no 4, pp. 28–34.

[5] Storozhenko L.I., Gasii G.M. and Gapchenko S.A. The new composite and space grid cable-stayed construction. Academic journal. Industrial Machine Building, Civil Engineering. PoltNTU. Poltava, 2014, no. 1, pp. 91–96.

[6] Nizhnik O.V Construction of steel and concrete composite girderless floor. Building construction. NIISK. Kyiv, 2013, no. 78(1), pp. 144–149.

[7] Storozhenko L.I. and Gasii G.M. Experimental research of strain-stress state of ferrocement slabs of composite reinforced concrete structure elements. Metallurgical and Mining Industry, 2014, no. 6, pp. 40–42.

[8] Стороженко Л.І., Гасій Г.М., Гапченко С.А. Просторові сталезалізобетонні структурно-вантові покриття: Монографія, Полтава: ТОВ «АСМІ», 2015, 218 с.

APPLYING VISIONARY CONCEPT DESIGN TO ENERGY EFFICIENT RESIDENTIAL AREAS

Jukka Laitinen
(jukka.laitinen@laurea.fi)

Tarja Meristö
(tarja.meristo@laurea.fi)

FuturesLabs CoFi
Laurea University of Applied Sciences

INTRODUCTION

In the EU 40% of the energy consumption and 36% of CO_2 emissions are related to buildings (European Commission). Therefore, the energy efficiency of the buildings, and more broadly residential areas, has an important role when looking for solutions to the problems caused by climate change.

In this paper we will focus on the energy efficiency of residential areas. By definition, a residential area is a physical and functional entity containing building blocks and also public and commercial services, such as grocery shops, day nurseries, schools, parks and recreation areas within a walking distance. The case areas in this paper consist of three residential areas in Finland which are in different phases of their life cycle.

The framework for this paper consists of future research combined to participatory design. The timeframe is reaching up to the next 20 years. As a methodological tool we apply visionary concept design (Kokkonen et al. 2005; Meristö et al. 2009). The data collection for future scenarios forming the basis for the visionary concept design process took place in a futurology study course held for 25 MBA students in Laurea University of Applied Sciences during spring 2016. The students, working in small groups, collected data and created alternative scenarios and visionary concepts for all three residential areas.

This aim of this paper is to introduce the methodological process and its outcomes. The results will open new views of the future when developing energy efficient residential areas from different perspectives including logistics, housing, energy, place and space, demographics, services, construction and safety & security. The results include also trends collected as background information for the scenarios. As a conclusion, a set of scenarios with visionary concepts will be presented.

RESEARCH DESIGN

The focus of this paper is in three research questions:

1. What are the drivers formulating the future alternatives for energy efficient residential areas?
2. How can thematic scenario alternatives support the participatory design?
3. What are the concrete visionary concepts supporting energy efficiency in the case areas?

The methods applied in this study are scenario approach and visionary concept design. Scenario working is a method within the field of futures research (Bell 1997, Masini 1993). Scenario working includes mapping alternative futures, identifying factors and development paths leading to different future outcomes. The action scenario approach (Meristö 1989) incorporates also the evaluation of the significance of the scenarios for the user. Finally, based on the evaluation necessary actions are suggested.

Scenarios are descriptions of different futures. Besides including the description of the competitive environment with factors like politics, economy, society, technology and environment the approach also incorporates the process of development. Scenarios are different from forecasts, as scenarios are usually not measured by their probability of occurrence (Schwartz 1996). Scenarios are not exact descriptions of the future; they are rather verbal descriptions of both qualitative and quantitative nature. Our framework is based on a multiple scenario approach i.e. at least two alternative scenarios are constructed. Furthermore, each scenario leads to various possible choices of strategies and alternative visionary concepts based on need in alternative futures (Kokkonen et al. 2005).

The method for creating visionary future product concepts consists of five main steps (Figure 1). The first step is the identification of change factors, which forms basis for the second step i.e. scenario building. The third step is the identification of product needs in each scenario. The fourth step is the actual generation of future product concepts based on the market need identified in each scenario. The fifth and last step of the method is the timing of R&D –activities and operations. This step also includes other considerations concerning the contribution the visionary concepts might have to the company's business planning or strategy (Kokkonen et al. 2005).

External change factors build up the framework for the scenarios and also for the visionary concepts. However, the factors are interrelated with the actors, and that is why pure objective knowledge about factors is not enough. Different actors have different interests, aims and needs. Therefore, it is important to take this actor-view into consideration when creating scenarios for the visionary concepts. It is preferable that the same group of people who are generating future concepts are also building the scenarios for the basis of the concepts phase. When people are involved into the process from the very beginning, they have time to assimilate the content of the scenarios. This boosts group members to create more and better ideas in the phase of concept generation (Leppimäki et. al. 2008).

There are several ways to present and illustrate the visionary concepts. However, the concept description should include at least the main features of the concept, estimations on its market potential and technical feasibility. These are the main dimension of the concept by which also a picture of the future operational environment is depicted. Further, illustrations, sketches, animations or other visual presentation material are excellent ways to communicate the concepts and related ideas (Leppimäki et. al. 2008).

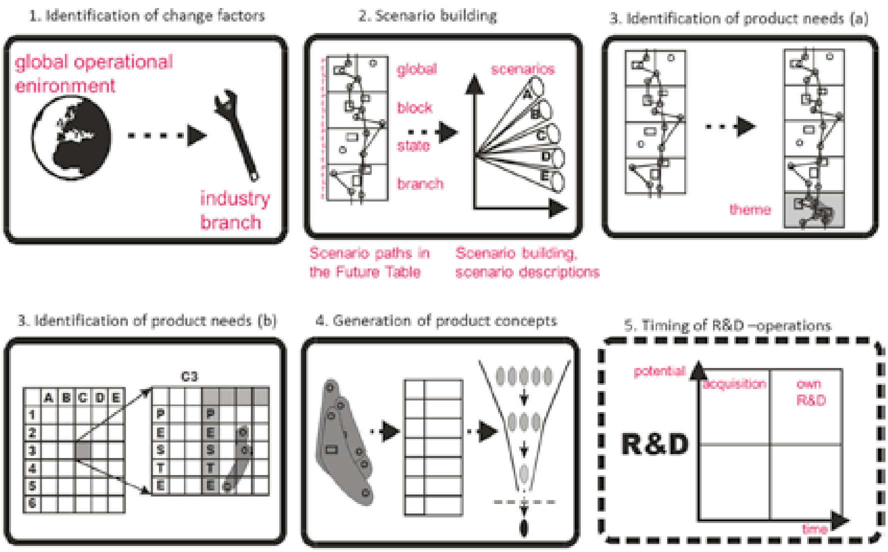


Figure 1. The five main steps to create visionary concepts (adapted from Kokkonen et. al. 2005).

The time perspective of the visionary concepts is long. Therefore, they are targeted at the markets of the future, realized with the technology of the future and guided by societal norms and legislation of the future. Consequently, some details and features of the concept are difficult to describe and are more or less a matter of imagination. Several benefits arise from the long time range which is an essential feature in visionary concepts. To begin with, visionary concepts enable systematic examination of alternative future developments because future scenarios are illustrations of the operational environment in the future. It also takes into account the driving forces (e.g. changes in values, technological breakthroughs and new markets) as well as market potential, uncertainty and challenges related to future in alternative scenarios. Moreover, visionary concepts enable product concept design and R&D for the future, over next product generation visualizes the future as products which are corresponding to the market needs (Leppimäki et. al. 2008).

CASE AREA DESCRIPTIONS

This study is based on the ongoing ELLI project financed by European Regional Development Fund ERDF. In the project there are three case residential areas which all are located in Southern Finland: Engelinranta in Hämeenlinna, Askonalue in Lahti and Peltosaari in Riihimäki.

Engelinranta in Hämeenlinna is located close to the city center by the lakeside. The size of the area is 47 hectares of which 23 hectares is land area and 24 hectares is water area. It has been planned to build apartments for about 2600 inhabitants. Additionally, there will be spaces for the different business activities. In the construction of Engelinranta, it is possible to follow the principles of the sustainable development because the area leans on existing community technical networks, services, street network, public transport and refreshment network.

Askonalue has a central location close to center of Lahti with good transportation connections. Askonalue is an old industrial area and its size is more than 30 hectares. A historical industry milieu and existing service and actor network of the area are a strong foundation for the regional development which is carried out in cooperation with the town inhabitants and other actors.

Peltosaari residential area in Riihimäki has been built in the immediate vicinity of the city center during 1970s and the 1980s. The strength of Peltosaari is its location being close to the city center and close to nature. The biggest problems are connected to the condition of the apartments and real estates, energy efficiency and to the social problems. The town of Riihimäki has committed itself strongly to develop Peltosaari to become an attractive and ecological residential area.

In ELLI project these areas will be analysed in order to find new business opportunities for cleantech field. In practice, the areas are still in planning phase.

DATA AND PROCESS

The data collection for future scenarios forming the basis for the visionary concept design process took place in a futurology study course held for 25 MBA students in Laurea University of Applied Sciences during spring 2016. The process consisted of six steps which were as follows:

1. Describing a residential area by core competence tree (adapted from Hamel & Prahalad 1996).
2. Collecting future data (megatrends, wild cards, weak signals) for scenario building. Structuring collected data into market / technology / society perspectives according to scenario filter model (Meristo et al. 2009).

3. Selecting drivers from market / technology / society perspectives and formulating alternative fourfold tables based on those drivers. Choosing one fourfold table for more specific processing and drafting alternative future scenarios by considering assumptions and consequences in each block.
4. Analysing a residential area by SWOT-analysis in alternative scenarios, i.e. recognizing strengths, weaknesses, opportunities and threats in each scenario.
5. Developing proactive and defensive action alternatives in each scenario, i.e. what to do to avoid threats or vice versa, how to exploit opportunities.
6. Creating visionary concepts responding the challenges recognized in each scenario. Those concepts were related to products, services, business models as well as other action models concerning the development of case areas towards sustainability.

RESULTS

In this paper the results focus on driving forces behind the scenarios and visionary concepts based on the scenarios. As explained in the previous chapter, the student groups collected future data of megatrends, wild cards and weak signals. At first they applied PESTE approach for data collection, i.e. including political, economic, social, technological and ecological factors. Then, they structured the data into market / technology / society perspectives and chose drivers for the scenarios. The summary of the main drivers are introduced in Table 1. It is remarkable that drivers covered all the dimensions - i.e. market, technology and society – which ensured varied viewpoints about the future even though the general focus was in energy efficient residential areas.

Table 1. Summary of the main drivers behind the scenarios (collected from Student Reports 2016).

Market	Technology	Society
• Ownership form of apartments • Citizen driven business • Sustainable economy • Sufficiency of space • Building types	• Robotics • Speed of adoption of new technology • Extent of technological exploitation • Humans vs. technology • Renewable vs non-renewable energy sources	• Services in residential areas • Communality • Socioeconomic situation of consumers • Basic values • Consumer habits • Reputation of residential area

Based on the drivers each group created alternative scenarios. After that, visionary concepts based on alternative thematic scenarios were constructed, e.g. from space & place perspective the area with skyscrapers based on lego-type system was imagined, including the monorail transportation network above the roofs. On the other hand, a group focusing on living theme produced a concept “together we are stronger” by using sharing economy concept at the level of residential area. Construction theme focused mostly on concepts utilizing robotics as stuntmen in dangerous tasks. Groups with logistics and services themes had smart concepts in the web for different purposes, including safety & security services (Student Reports 2016).

As an illustrative example, we present the scenarios and visionary concepts from the group focusing on the energy theme. The main drivers behind the scenarios were energy sources (vertical axis) and consumer habits (horizontal axis). As a result there are four alternative scenarios which are introduced in Figure 2.

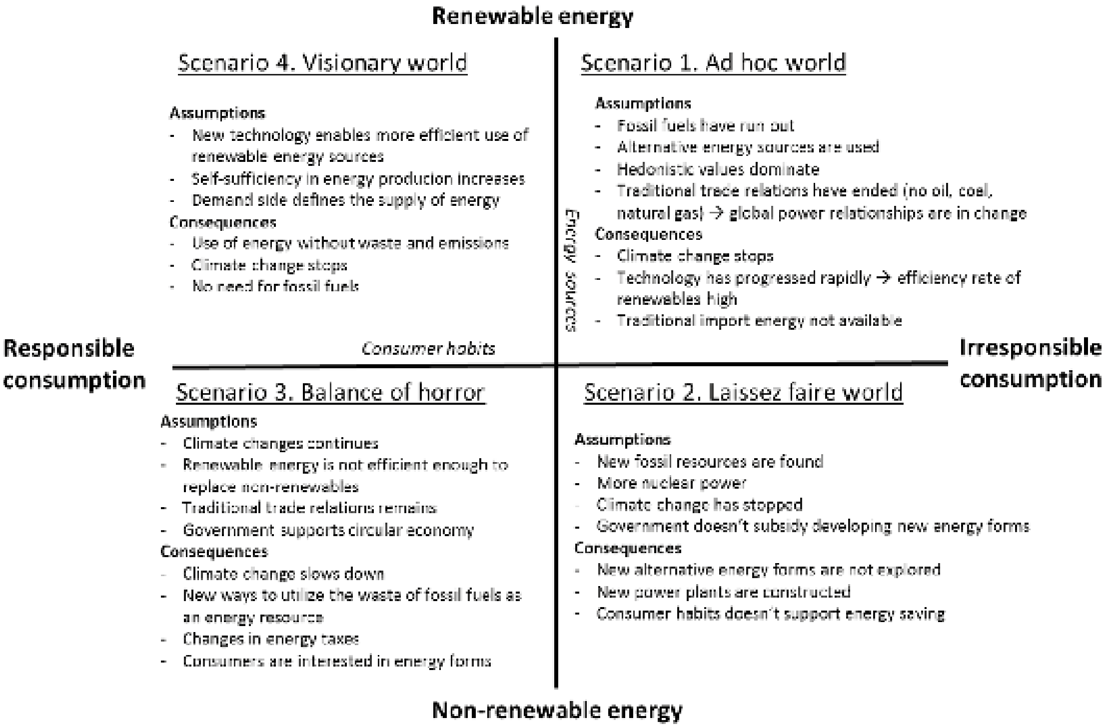


Figure 2. Scenario examples based on group work with energy focus (Student Reports 2016, Lajunen et. al. 2016).

Scenarios 1. Ad hoc world and Scenario 4. Visionary world have the focus in renewable energy where as in Scenario 2. Laissez faire world and Scenario 3. Balance of horror the emphasis is on non-renewable energy. Additionally, consumer habits cause variety to the scenarios, depending on whether consumers are responsible or irresponsible. Visionary concepts were created for each scenario (Figure 3).

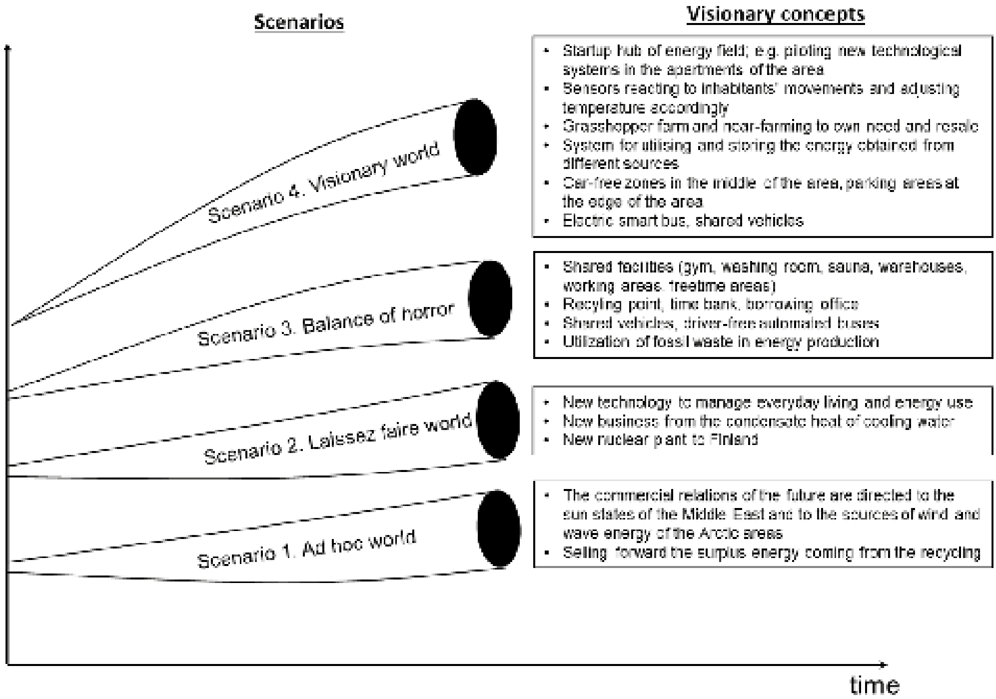


Figure 3. Visionary concepts related to the energy theme (adapted from Student Reports, Lajunen et. al. 2016).

CONCLUSION

Even if the focus is in energy efficient residential area the drivers shaping the future can be very diverse. In this study the driving forces were divided according to the scenario filter model including market, technology and society dimensions. The market drivers include factors such as ownership form of apartments, citizen's role, sustainability in business, sufficiency of space and type of buildings. On the other hand, many of the drivers are related to technology. An essential driver regarding the future is the role between renewable and non-renewable energy forms. Other technology-related drivers consist e.g. of robotics, extent of technological exploitation, the speed of implementing new technological solutions and role between humans and technology. Additionally, society related drivers are notable including e.g. services provided in residential areas, communality, basic values and life styles.

This study was carried out by student groups and each group had their own thematic viewpoint. Thematic groups dealt with logistics, housing, energy, place and space, demographics, services, construction and safety & security. Alternative scenarios from each thematic perspective were constructed. The scenarios formed in each group shared a language and basis for concept design work. Timeframe to the future for the next 20 years helped participants to get feet from the ground and think also unthinkable solutions and concepts.

Some of the concepts may be suitable only for one certain scenario whereas some concepts may suit several or all scenarios. For example, shared facilities are a must in Scenario 3. Balance of horror, but they work well also in other scenarios. On the other hand, startup hubs in Scenario 4 require more sophisticated conditions to work.

The advantage of visionary concept design is that it enables systematic examination of alternative future developments. Future scenarios are illustrations of the operational environment in the future, which also takes into account the driving forces from different perspectives. Thematic focus of each group opened also new insights into residential areas and their energy efficiency, even more broadly, to their sustainable development in the future.

REFERENCES

Bell, W. (1997) Foundations of Futures Studies I: History, Purposes, Knowledge. New Brunswick, NJ: Transaction Publishers, 1997.

European Commission (2016) https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

Hamel, G. & Prahalad, C.K. (1996). Competing for the Future. Harvard Business School Press.

Kokkonen, V., Kuuva, M., Leppimäki, S,, Lähteinen, V., Meristö, T., Piira, S., Sääskilahti, M. (2005). Visioiva tuotekonseptointi - työkalu tutkimus- ja kehitystoiminnan ohjaamiseen. (Visionary concept design – a tool for steering R&D activities). Technology Industry Association in Finland. (In Finnish).

Leppimäki, S., Laitinen, J., Meristö, T., Tuohimaa, H. (2008) Visionary Concept: Combining Scenario Methodology With Concept Development. In Wagner, C. (ed.) Seeing the Future Through New Eyes. World Future Society.

Masini, E. (1993) Why Futures Studies? Grey Seal, London.

Meristö, T. (1989) Not Forecasts but multiple scenarios when coping with uncertainties in the competitive environment. European Journal of Operatios Research Vol 38, pp. 350-357 ,1989.

Meristö T., Leppimäki S., Laitinen J. & Tuohimaa H. (2009) Scenario Filter Model: The framework to generate scenarios and select visionary concepts for development. ISPIM conference proceedings.

Schwartz, P. (1996) The Art of the Long View: Planning for the Future in an Uncertain World New York: Currency Doubleday.

Student Reports (2016) for Futurology study module. Laurea University of Applied Sciences, Finland (unpublished student reports).

- Färm, M., Salminen, S. & Aro, J. (2016) Demographics theme.
- Heikkilä, L., Savolainen, S. & Väisänen, M. (2016) Space & place theme.
- Ilveskoski, A-M., Palotie, P. & Sburatura, M. (2016) Logistics theme.
- Javanainen, K., Mikkola-Ahokas, A. & Nurmi, T. (2016) Security & safety theme.
- Lager, N., Hirsso, J. & Kleimola, M. (2016) Construction theme.
- Lajunen, H., Rautemaa, M., Sainio, J. & Velling, E. (2016) Energy theme.
- Luostarinen, K., Länsivire, H. & Norppa-Röpelinen, P. (2016) Living theme.
- Rantanen, K., Rinkinen, N. & Rostedt, P. (2016) Service theme.

CLEANTECH BUSINESS OPPORTUNITIES IN THE FUTURE

Tarja Meristö
(tarja.meristo@laurea.fi)

Jukka Laitinen
(jukka.laitinen@laurea.fi)

FuturesLabs CoFi
Laurea University of Applied Sciences

ABSTRACT

In this paper we will focus on cleantech business opportunities (Meristö & Laitinen 2014) which the future will provide for the companies as well as on the skills and capabilities required to exploit those opportunities. The research questions are as follows:

1. What are the main drivers for the future concerning energy-efficient and sustainable solutions?
2. What are the skills and competences needed to meet the future challenges in this field?
3. What are the barriers and / or enablers when developing cleantech business for the future?

The data collected for this research paper consist of web-survey replies received from industry leaders, governmental decision makers, NGO representatives and individual experts from this field. The main drivers vary from international environmental agreements to consumer market behavior, depending on how strictly the legislation, but also the purchasing power of consumers will guide the development. Skills concerning digitalization and automation, but also marketing and communication are important among skills concerning new materials and renewable energy development work. Taboos in this field are discussed, too.

INTRODUCTION

Environmentally friendly solutions in different business sectors have been sought during the last few decades. Energy sector and the process industry have been forerunners in developing eco-efficient production processes from the 1960´s. For example, pulp and paper industry has faced environment, health and safety issues very early in 1970´s in the consumer market. In the late 1980´s, and even more during 1990´s and in the new millennium, climate change discussion took a big role in everyday media. All businesses and industrial sectors had to meet the challenges concerning corporate social responsibility (Meristö 2013). Today the new economy (Erber & Hageman 2005) has been replaced by circular economy (Pearce & Turner 1989) and all the industries are looking for new opportunities from sustainable solutions (Kettunen 1998), in processes and products and services.

Value chain throughout the whole life-cycle includes many different opportunities for the growth of cleantech business. In the beginning, the input of raw materials and energy is the key enabler (or barrier) to cleantech business. The more renewables are used in the energy side, the cleaner the business is in the long run. Also, the more renewables or recycled materials are used, the greater will be the opportunities for the cleantech defined business. Logistics and transportation along the value chain constitute a remarkable factor when defining the sustainability rate of the businesses or communities. The sustainable community, by definition, has at least a chance for logistics with no emissions, i.e. safe routes for walking and bicycling or electric car network. Also, the construction materials and multi-perspective energy solutions based on renewables and bio-energy will form the basis for green and clean business opportunities in the construction sector and in community planning, too. (Tuohimaa et. al. 2011; Kettunen et. al. 2015)

RESEARCH DESIGN

The framework for this study consists of futures research methodology (Masini 1993) including mega- and mini-trend analysis (Vanston & Vanston 2011) and scenario approach (Meristö et.al. 2012) concerning especially the future of residential areas and their opportunities for cleantech business. Another part of the framework includes the skills and competences (Meristö et. al. 2015) required to exploit these opportunities not only at company level but at national level, too.

The paper focuses on cleantech business opportunities which the future will provide for the companies as well as on the skills and capabilities required to exploit those opportunities. The research questions are as follows:

1. What are the main drivers for the future concerning energy-efficient and sustainable solutions?
2. What are the skills and competences needed to meet the future challenges in this field?
3. What are the barriers and / or enablers when developing cleantech business for the future?

The data collected for this work comprises mostly on replies from a web-survey run in May-September 2016 by us in the project ELLI financed by European Regional Development Fund ERDF. The survey has been sent to the actors in the field of sustainable business and energy-efficient solutions in South Finland in different regions, namely Lahti, Riihimäki, Hämeenlinna and Lohja region with their surroundings.

RESULTS

The survey was sent to the actors from the cleantech cluster in many roles: companies from different industries, government organizations at local, regional and national level, research institutes and educational organizations as well as NGOs and experts and active citizens from this field. Altogether, 50 replies were received until the 20 September 2016.

From the respondents about one third came from different industries (36%) and almost another third from research and education (30%), 14% came from decision making side, 10 % from active citizens and 8% were experts. Some of the respondents represented themselves in several different roles. None of the replies were from EU level nor from NGOs in the field of environment, inhabitants´ or lobbying interests. Two thirds from the replies were male, one third female. Most answers came from the Lahti region (33%) and from Western Uusimaa region (29%) and the rest were from Hämeenlinna (13%) and Riihimäki (4%) region or other places in Finland (21%).

The survey included six different research areas of questions: 1) Level of cleantech competences in Finland, 2) Special expertise / skills in cleantech in that region, 3) Key actors in energy-efficient residential regions, 4) Taboos, 5) Future Energy Solutions in Residential areas, 6) Key Trends concerning Future Energy Solutions. Also background information from the replier and open feedback were asked.

The results in this paper are divided into three parts, by answering the research questions as follows. First, the main drivers for the future concerning energy-efficient and sustainable solutions will vary from today to the future according to the next diagram, where the average values of the survey results are presented (Figure 1).

The future will differ from the present concerning almost all the factors asked in the survey: Time frame of the decision–making from short term will move towards long term, the market of the Finnish cleantech industry will focus more on the global instead of the local market, role of subventions concerning energy efficiency will decrease in the future, willingness to have residential areas without cars will increase in the future, energy savings will be easily realized by automation in the future, the focus of energy sources will move from non-renewables to renewables, the climate change issues will worry in the future not only experts but even ordinary citizens everywhere and finally, the role of circular economy will be a remarkable industry instead of a present boom phenomenon and also the skills and competences related to the cleantech in Finland will be broader than today. Only the norms of the international environmental agreements appear to be almost the same in the future. In the same way, the willingness to pay more for green solutions does not change a lot in the future from that which exists today. Lifestyle in Finland will continue both in urban environments and in the countryside as well, although at global level the urbanization is a strong megatrend.

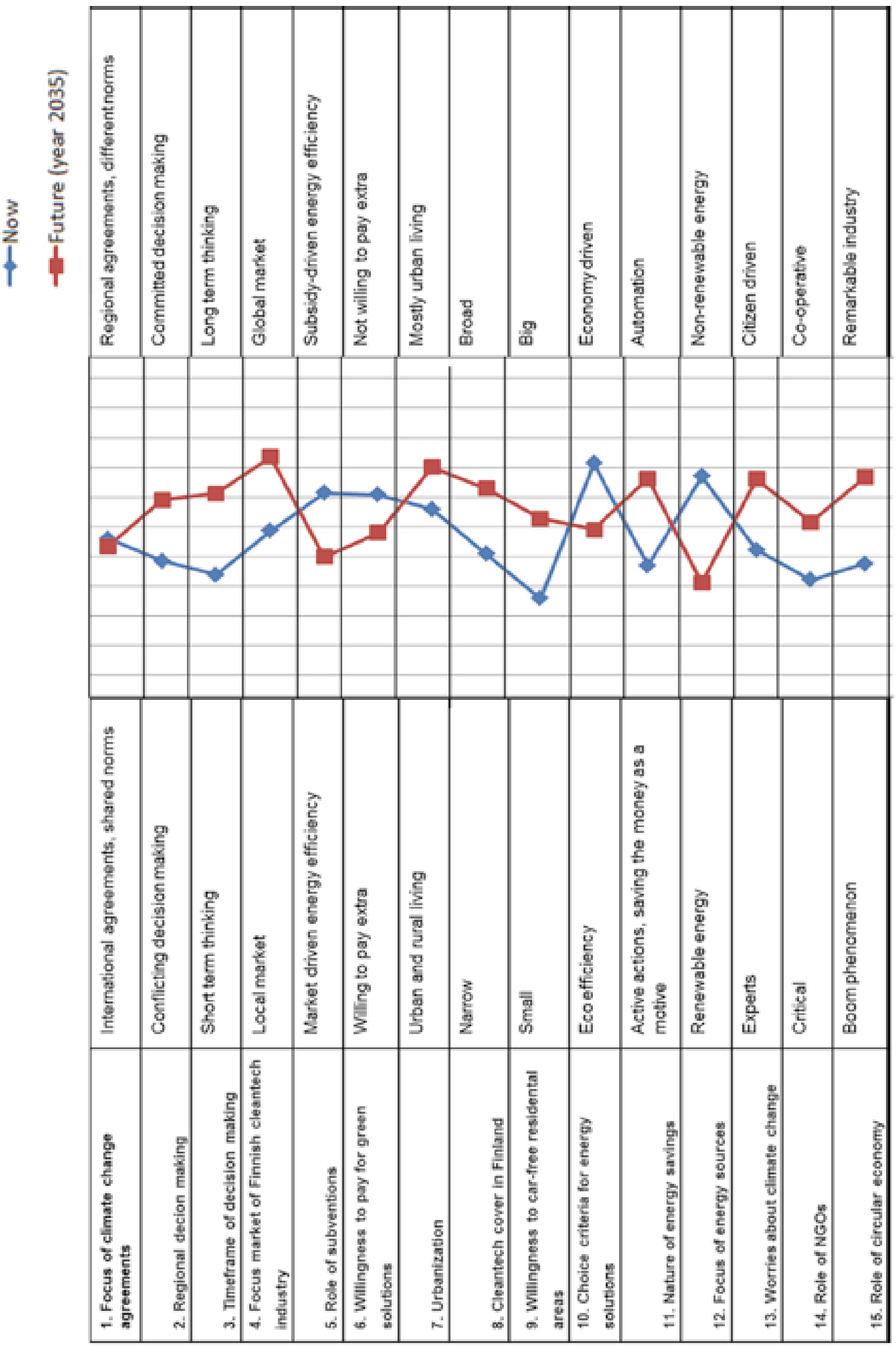


Figure 1: Main drivers for the future and the directions of the change needed.

Second result from the study, concerning the skills and competences needed to meet the future challenges in this field today and in the future, is as follows (Figure 2).

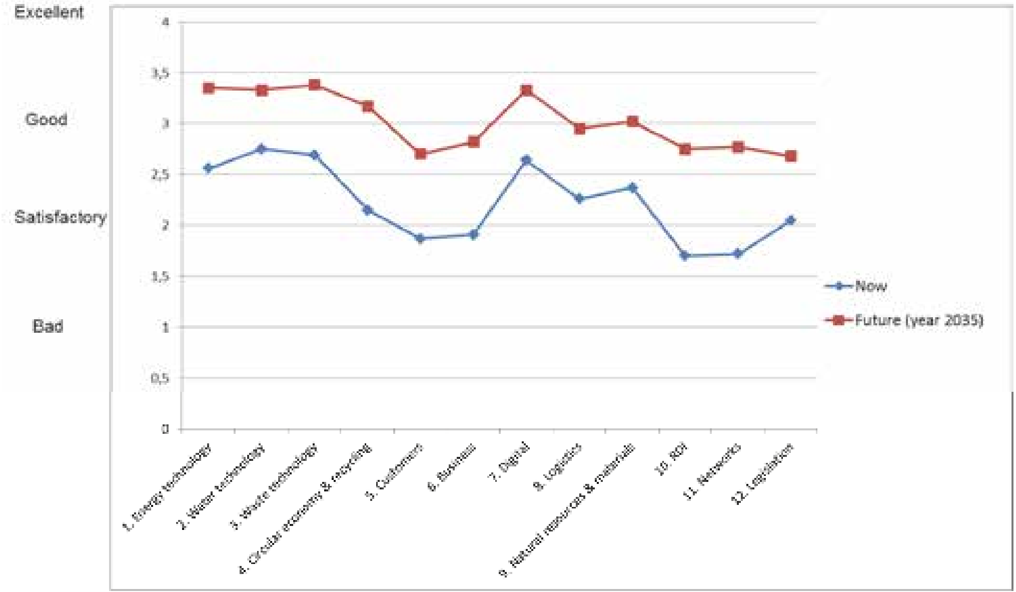


Figure 2: Skills and competences in clean tech industry needed in the future.

The scale to estimate the level of the skills and competences in the cleantech is from 1 to 4: 1 = bad, 2= satisfactory, 3= good and 4= excellent. None of the listed skills and competences reached the level good (number 3) in this survey. Energy technology skills, water technology skills, waste technology skills and digital skills and competences as well as competences concerning natural resources and materials were estimated approximately to the level 2.5 (almost good). The weakest evaluation points went to the RDI skills, network skills, customer understanding and business skills, all getting values under the satisfactory level 2. Legislation skills reached barely satisfactory level. The estimations concerning the future statement did increase the evaluation points throughout the whole list of competences. The highest ranking, level 3.5 belongs to the waste technology skills and competences and close to that were ranked also regarding energy technology skills and water technology skills. In the future, none of the skills were evaluated under the level 2 (satisfactory), but under the level 3 (good) in the future still are the competences having the lowest score today, namely skills concerning e.g. customer understanding, business RDI , networking and legislative issues. Outside the given list one of the replies mentioned the branding skills, still being very low concerning the Finnish cleantech industry.

Third, the barriers and enablers when developing cleantech business for the future were found among the taboos recognized in this survey, but also from the key actors estimated in this field. The most powerful actors are decision-makers at EU and national level, but also regional decision-makers as well as the companies from this field (Figure 3). This result means that still the focus is on the enablers and just after that, the business will have opportunities to develop.

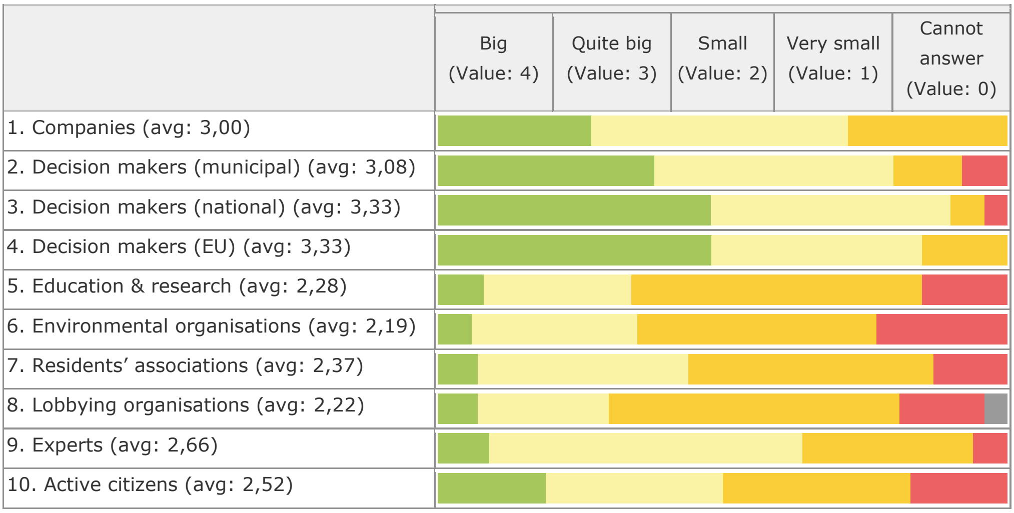


Figure 3: Key actors in the power game concerning the future of energy-efficient regions.

The barriers and enablers related to the taboos were also recognized in this survey. The subvention driven policy seems to be a barrier for the market driven growth, but also on the industry side there is a lack of holistic view to the branch and holistic solutions are still rare; instead of the systematic, multidisciplinary co-operation in the international networks many of the companies and entrepreneurs in this field work alone, far from the market and customers. Also, the long-term life-cycle analysis in the eyes of the sustainability is missing. Perhaps active citizens together with research actors and other experts could raise these issues more in the table in the future, when planning and building new residential areas. Environment, health and safety (EHS) are related to each other and customers with high awareness of the risks are in the future probably willing to pay to reduce these risks, too. At the moment, active citizens in this field still can get a sign of a green person without a touch of the reality, was one of the barriers mentioned in the survey replies.

CONCLUSIONS

According to the survey results, no one estimated the significance of non-renewable energy sources very high in the future and almost all of the replies ranked it low or even less significant, when developing residential areas (Figure 4). On the other hand, solar power and geothermal energy were evaluated to be very significant or at least with a significant score in the energy palette in the future. Bio-energy based on waste received a few higher points than bio-energy based on the wood. The figure as follows will summarize these estimates concerning different energy sources and their importance in the future after next 20 years.

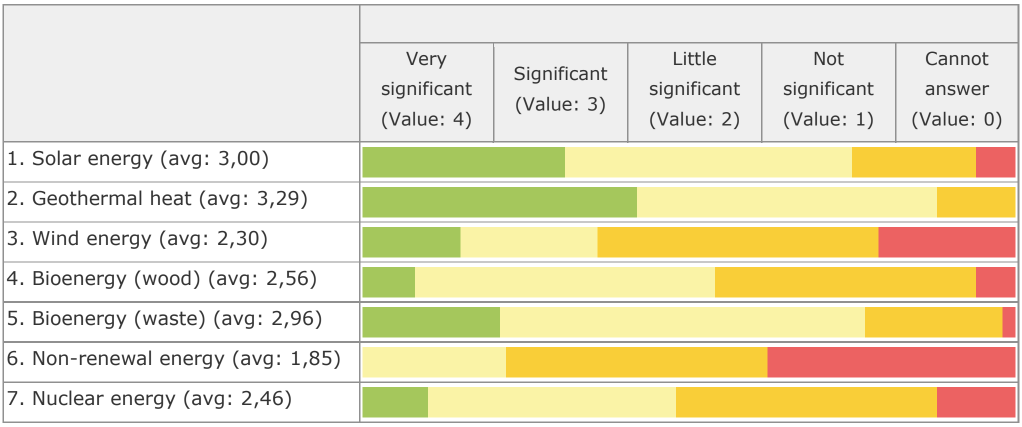


Figure 4: The significance of the alternative energy solutions of residential areas in the future.

The holistic view in the long-run, including natural resources and economic calculations at global level will open the eyes for new opportunities in the cleantech sector. Its impact on the globe and its state of the art will be dramatic, if developing business with an attitude of saving the world. Also, the skills and competences have to be updated, and that will require changes in the education and government policy as well. Also, the networking activities have to be developed to the everyday life level, without handicap in attitudes in multicultural world.

REFERENCES

Erber, G. & Hagemann, H. (2005) The New Economy in a Growth Crisis. In Huebner. K. (ed.) The New Economy in Transatlantic Perspective. Taylor and Francis Inc., New York, USA.

Kettunen, J. (1998) Can Finland Still Live from the Forest? Finnish Forest Cluster to 2020, pp 302-339, in a Book Green Kingdom, eds. Reunala, A, Tikkanen, I,

Åsvik, E. Otava Ltd..

Kettunen, J., Meristö, T. & Laitinen, J. (2015) . Bioenergy Scenarios 2033 – a Platform for the Innovation. In Proceedings of The XXVI ISPIM Innovation Conference held in Budapest (Hungary) on 14 June to 17 June 2015. Editors:

Huizingh Eelko, Torkkeli Marko, Conn Steffen, and Bitran Iain. LUT Scientific and Expertise Publications 40. Tutkimusraportit – Research Reports.

Masini, E. (1993) Why Futures Studies? Grey Seal, London.

Meristö, T. (2013) Yritysten planetaarinen vastuu ja sen kehittyminen yrityskentässä. Futura 2/2013, 48-51. (Planetary Corporate Responsibility and its Development in the Field.)

Meristö, T. & Laitinen, J. (2015) Future Skill Profiles – a Key to Renew Marine Industry. In Proceedings of The XXVI ISPIM Innovation Conference held in Budapest (Hungary) on 14 June to 17 June 2015. Editors: Huizingh Eelko, Torkkeli Marko, Conn Steffen, and Bitran Iain. LUT Scientific and Expertise Publications 40. Tutkimusraportit – Research Reports.

Meristö, T. & Laitinen, J. (2014) Kestävän liiketoiminnan mahdollisuudet Länsi-Uudellamaalla – nykytila ja tulevaisuuden näkymiä. (Opportunities for Sustainable Business in Western Uusimaa County – a Present Situation and Alternative Future Views). Novago, Lohja (in Finnish).

Meristö, T., Laitinen, J. & Tuohimaa, H. (2012) Scenario Filter Model as an Innovation Catalyst. The Proceedings of the 5th ISPIM Innovation Symposium, Seoul, Korea - 9-12 December 2012.

Pearce, D & Turner, R. K. (1989). Economics of Natural Resources and the Environment. Johns Hopkins University Press.

Tuohimaa, H., Meristö, T., Kettunen, J. & Laitinen, J. (2011) Sustainable Community Scenarios – A Challenge for Innovation Management in the Public Sector. Proceedings of the XXII ISPIM Conference, 12-15 June 2011, Hamburg, Germany.

Vanston, J. & Vanston, C. (2011) Minitrends: How Innovators & Entrepreneurs Discover & Profit From Business & Technology Trends. TFI Texas.

MOMENT-ROTATION BEHAVIOUR OF WELDED TUBULAR HIGH STRENGTH STEEL JOINTS

Markku Heinisuo, Marsel Garifullin, Kristo Mela, Teemu Tiainen, Timo Jokinen
Tampere University of Technology, Korkeakoulunkatu 10, FI-33720, Tampere, Finland

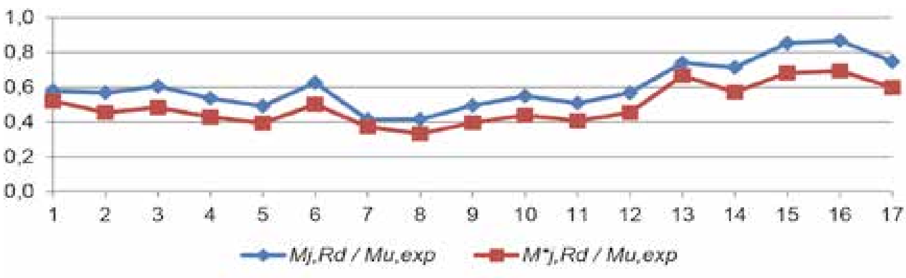
The field of applications of tubular structures covers a large range of structures, such as bridges, lattice masts, buildings and large span structures. Implementing high strength steel (HSS) to tubular joints allows reducing the consumption of metal (Johansson 2003), however it implies increased material and manufacturing costs, which must be considered when economical designs are pursued. In cost and emission optimization of HSS structures an essential task is the evaluation of the feasibility of the structure. In cost and emission analysis one important issue is welding duration and energy consumption using different welding technologies with different base materials, weld sizes and welding positions.

Any new design methods have to be validated with experiments. The overall research of tubular joints was mainly adapted by Wardenier (1982) who first proposed the design formulas based on the classical yield line theory. The experiments for welded tubular moment joints have been presented in (Brockenbrough 1972), (Korol et al. 1977), (Kanatani et al. 1980), (Yura et al. 1981), (Ono et al. 1991), (Ishida et al. 1993), (Davies et al. 1996), (Owen et al. 2001), (Christitsas et al. 2007), (Fadden et al. 2015), (Chen et al. 2015), and (Tong et al. 2015). Tests for stainless steel SHS welded joints are presented in (Feng and Young 2006). However, experiments of welded HSS tubular moment joints cannot be found in published literature.

The design of joints mean checks of resistance, stiffness and ductility. The moment resistance of a joint is the most important quantity in design. The rotational stiffness is needed when the global structural analysis model based on beam elements is made. The rotational stiffness has a great effect when cost optimal solutions are searched both in sway frames (Anderson et al. 1997), (Grierson and Xu 1993), (Simoes 1996), (Weynand et al. 1998), (Haapio et al. 2011) and in non-sway frames, as well (Bzdawka 2012). The rotational stiffness has an influence also on the buckling length of the members (Boel 2010), (Snijder et al. 2011) and (Heinisuo and Haakana 2015). It has been found theoretically (Heinisuo et al. 2016), that the weld size has a large effect on the initial rotational stiffness of welded tubular moment joints. Very few investigations have been conducted to explore the moment-rotation behaviour of welded joints made of HSS. This research involves 17 tests performed to observe the moment-rotation relationship and ductility of the joints. The experimental data are compared with the results of comprehensive finite element modelling (FEM) and manual calculations according to the Eurocode.

MAIN RESULT

The method for calculation of the moment resistance proposed in (EN 1993-1-8, 2005) allows getting rather safe results, the average $M_{j,Rd}$ / $M_{u,exp}$ ratio is 0.61 (Fig. 1). Applying the correlation coefficient related to HSS makes the results very conservative ($M^*_{j,Rd}$ / $M_{u,exp}$ ratio 0.50). This shows that there is no need to reduce the moment resistance of HSS joints as prescribed in Eurocodes..



The full paper will present the results including the following:

- Moment-rotation relationship of the joints;
- The effect of weld size on the initial rotational stiffness;
- The ductility of the joints.

Another aim of the tests was to study the effect of the weld size on moment of resistance, rotational stiffness and ductility of the joint.

REFERENCES

Anderson, D., Hines, E.L., Arthur, S.J. and Eiap, E.L. 1997. Application of artificial neural networks to the prediction of minor axis steel connections. *Computers & Structures* 63(4): 685–692.

Boel, H. 2010. Buckling Length Factors of Hollow Section Members in Lattice Girders. Ms Sci thesis, *Eindhoven*: *Eindhoven University of Technology*.

Brockenbrough, R.L. 1972. Strength of Square-Tube Connections under Combined Loads. *Journal of the Structural Division* 98(12): 2753–2768.

Bzdawka, K. 2012. Optimization of Office Building Frame with Semi-Rigid Joints in Normal and Fire Conditions,. *PhD Thesis, Tampere University of Technology, Publication 1038*.

Chen, Y., Feng, R. and Wang, J. 2015. Behaviour of bird-beak square hollow section X-joints under in-plane bending. *Thin-Walled Structures* 86: 94–107.

Christitsas, A.D., Pachoumis, D.T., Kalfas, C.N. and Galoussis, E.G. 2007. FEM analysis of conventional and square bird-beak SHS joint subject to in-plane bending moment — experimental study. *Journal of Constructional Steel Research* 63(10): 1361–1372.

Davies, G., Owen, J.S. and Kelly, R. 1996. Bird beak T-joints in square hollow sections: a finite element investigation. In *Proceedings of the International Offshore and Polar Engineering Conference. Int Soc of Offshore and Polar Engineerns (ISOPE)*, pp. 22–27.

Fadden, M., Wei, D. and McCormick, J. 2015. Cyclic Testing of Welded HSS-to-HSS Moment Connections for Seismic Applications. *Journal of Structural Engineering* 141(2): 04014109.

Feng, R. and Young, B. 2006. Tests of stainless steel RHS X-joints. *Welding in the World* 50(SPEC. ISS.): 250–257.

Grierson, D.E. and Xu, L. 1993. Design optimization of steel frameworks accounting for semi-rigid connections. In G. I. N. Rozvany, ed. *Optimization of Large Structural Systems, Volume II. Dordrecht*: *Kluwer Academic Publisher*, pp. 873–881.

Haapio, J., Jokinen, T. and Heinisuo, M. 2011. Cost simulations of steel frames with semi-rigid joints using product model techniques. In L. Dunai, M. Ivanyi, K. Jarmai, N. Kovács, & L. G. Vigh, eds. *Proceedings of EUROSTEEL 2011. Brussels*: *ECCS*, pp. 2151–2156.

Heinisuo, M., Garifullin, M., Jokinen, T., Tiainen, T. and Mela, K. 2016. Surrogate modeling for rotational stiffness of welded tubular Y-joints. *Proceedings of The Eighth International Workshop on Connection in Steel Structures (Connections VIII).*

Heinisuo, M. and Haakana, Ä. 2015. Buckling of members of welded tubular truss. *Nordic Steel Construction Conference 2015.*

Ishida, K., Ono, T. and Iwata, M. 1993. Ultimate strength formula for joints of new truss system using rectangular hollow sections. In *Proceedings of 5th International Symposium on Tubular Structures*. pp. 511–518.

Johansson, B. 2003. Use and design of high strength steel structures. *Revue de Metallurgie. Cahiers D'Informations Techniques* 100(11): 1115–1123+vi–ix.

Kanatani, H., Fujiwara, K., Tabuchi, M. and Kamba, T. 1980. Bending tests on T-joints of RHS chord and RHS or H-shape branch. *CIDECT Program 5AF (March 1981).*

Korol, R.M., El-Zanaty, M. and Brady, F.J. 1977. Unequal width connections of square hollow sections in Vierendeel trusses. *Canadian Journal of Civil Engineering* 4(2): 190–201.

Ono, T., Iwata, M. and Ishida, K. 1991. An experimental study on joints of new truss system using rectangular hollow sections. In *Tubular Structures. 4 th International Symposium*. pp. 344–353.

Owen, J.S., Davies, G. and Kelly, R.. 2001. The influence of member orientation on the resistance of cross joints in square RHS construction. *Journal of Constructional Steel Research* 57(3): 253–278.

Simoes, L.M.C. 1996. Optimization of frames with semi-rigid connections. *Computers & structures* 60(4): 531–539.

Snijder, H.H., Boel, H.D., Hoenderkamp, J.C.D. and Spoorenberg, R.C. 2011. Buckling length factors for welded lattice girders with hollow section braces and chords. *Proceedings of Eurosteel 2011*: 1881–1886.

Tong, L., Xu, G., Liu, Y., Yan, D. and Zhao, X.-L. 2015. Finite element analysis and formulae for stress concentration factors of diamond bird-beak SHS T-joints. *Thin-Walled Structures* 86(3): 108–120.

Wardenier, J. 1982. Hollow Section Joints. Doctoral dissertation, *Delft*: *Delft University of Technology. 544 p.*

Weynand, K., Jaspart, J.-P. and Steenhuis, M. 1998. Economy studies of steel building frames with semi-rigid joints. *Journal of Constructional Steel Research* 46(1-3): 85.

Yura, J.A., Edwards, I.F. and Zettlemoyer, N. 1981. Ultimate Capacity of Circular Tubular Joints. *Journal of the Structural Division* 107(10): 1965–1984.

STEEL JOINTS WITH BEAMS OF UNEQUAL DEPTH USING CRUCIFORM ELEMENTS FOR FRAME ANALYSIS

Eduardo Bayo
University of Navarra

The behaviour of joints exerts an important influence on the overall performance of steel and composite structures. Modern codes, including Eurocodes 3 (EC3) and Eurocode 4 (EC4), have included advances in research for modelling of joints to be used in common practice. The method adopted in EC3 and EC4 to characterize the connections is the so-called component method.

The development of the component method for the characterization of steel joints (Eurocode 3) has led to the use of mechanical models, composed of springs and rigid bars for frame analyses. However, this adds complexity, numerical overhead —consequence of the large number of degrees of freedom — and possible round off errors (due to the rigid bars) in the solution process.

One of the most important components is the column web panel in shear, and its behaviour has been investigated thoroughly for the case of single rectangular shear panels arising when the beams have equal depths. However, the case of trapezoidal and double column panels, formed by beams of different depths at each side of the column, has not been researched as much.

In order to isolate the shear behaviour from other components, diagonally and horizontally stiffened beam to column connections with commercial sections are experimentally tested.

Also, finite element modelling and analyses are carried out to compare results. Mechanical models are proposed and a parametric study is performed by means of calibrated finite elements models to characterize the different components, and define the analytical expressions for the stiffness and resistance of the proposed mechanical model.

With the aim of avoiding the problems mentioned above, generalized cruciform finite elements with 4 nodes and 12 degrees of freedom (for the 2D case) are proposed. These cruciform elements are also suitable for semi-rigid connections and can be used for the global analysis of semi-rigid steel frames. The elements are capable of modelling rectangular, trapezoidal and double rectangular web panels, arising in internal joints with beams of different depth.

The characteristics of these elements (stiffness and resistance) are generated from the mechanical models by means of an efficient displacement based modal approach. All the forces and moments coming from the adjacent beams and columns concur at the joint, therefore, the complete force field in the panel zones is known with no need for a transformation parameter used in EC3-Part 1.8. In addition, since the real dimensions of the joint are being considered, the eccentric moments are automatically taken into account. Also, the interaction between the deep and the shallow sides of column double panels are taken into account. Numerical simulations are carried out that show the validity and efficiency of the proposed approach.

The full paper will present the behaviour of the proposed mechanical model. It is shown that this general cruciform element is suitable for simple, rigid and semi-rigid connections and can be used for global analysis steel frames.

CRUCIFORM FINITE ELEMENTS FOR THE MODELLING OF STEEL JOINTS IN FRAME ANALYSIS

Eduardo Bayo
University of Navarra

The development of the component method for the characterization of steel joints (Eurocode 3) has led to the use of mechanical models, composed of springs and rigid bars for frame analyses. However, this adds complexity, numerical overhead — consequence of the large number of degrees of freedom — and possible round off errors (due to the rigid bars) in the solution process.

With the aim of avoiding these problems generalized cruciform finite elements with 4 nodes and 12 degrees of freedom (for the 2D case) are proposed. These cruciform elements are also suitable for semi-rigid connections and can be used for the global analysis of semi-rigid steel frames. The elements are capable of modelling rectangular, trapezoidal and double rectangular web panels, arising in internal joints with beams of different depth.

The characteristics of these elements (stiffness and resistance) are generated from the mechanical models by means of an efficient displacement based modal approach. All the forces and moments coming from the adjacent beams and columns concur at the joint, therefore, the complete force field in the panel zones is known with no need for a transformation parameter used in EC3-Part 1.8. In addition, since the real dimensions of the joint are being considered, the eccentric moments are automatically taken into account. Also, the interaction between the deep and the shallow sides of column double panels are taken into account. Numerical simulations are carried out that show the validity and efficiency of the proposed approach.

RECENT RESEARCH AND DESIGN DEVELOPMENTS IN STEEL AND COMPOSITE STRUCTURES AT UPC

Mirambell E., Real E. and Chacón R.
Department of Civil and Environmental Engineering
Universitat Politècnica de Catalunya, BarcelonaTech

Recent research and design developments of the Steel and Composite Division group of the Department of Civil and Environmental Engineering (*UPC, Barcelona Tech*) encompasses several areas of expertise. Particular research focus includes i) Structural behavior of stainless steel, ii) Stability and design developments of plated structures and iii) Steel-concrete composite members. The research in steel and composite structures covers experimental, numerical and theoretical studies on the behavior and analysis for safe and sustainable design.

Stainless steel design has been studied for two decades by the group within the frame of several European and National research projects. The projects include the Theoretical and experimental study on instability of stainless steel structures (DGES PB95-0772), Structural applications of plated stainless steel girders (MAT 2000-1000) and Structural analysis of ferritic stainless steel members such as tubes, slabs and hat-sections (BIA 2012-036373 and SAFSS 2010 RFS-PR-09032). On the other hand, the Steel and Composite Division group has been involved in several valorization projects funded by RFCS-European Commission: Development of the use of stainless steel in construction (ECSC Contract 1999-7215-PP/056), Structural design of cold-worked austenitic stainless steel (RFS2-CT-2005-00036), and Promotion of new Eurocode rules for structural stainless steels (RFCS-2015, RFCS RFS-AM-709600). Research has resulted in a considerable amount of scientific production (journal papers, conference proceedings, design manuals and participation in European committees for standardization and design such as EN1993-1-4 Working Group).

Plated structures have been actively studied for more than two decades as part of separate research activities. National projects related to instability problems in plates (DGICYT PB90-0604), to hybrid steel plate girders (BIA 2004-04673) and to steel tapered plate girders (BIA 2008-01897), among others, have provided a robust platform to the group for the development of theoretical, experimental and numerical expertise in the field. Research has also resulted in a considerable amount of scientific output (journal papers, conference proceedings, design manuals and participation in European committees for standardization and design such as TC8 and TWG 8.3 of ECCS, and EN 1993-1-1 Working Group WG 1 and EN 1993-1-5 Working Group WG 1-5).

Composite structures have also been studied as part of research projects related to concrete-filled steel tubes (Safety and serviceability of integral railway bridges in front of accidental actions: Research for design criteria and construction, 2007-2011, Project 51/07), to stainless steel-concrete composite slabs (SAFSS project) and to a vast array of experimental applications including push-out and pull-out tests, composite action with shear connectors and thermally-induced deformations within composite elements. Research has resulted in journal papers, conference proceedings and experimental expertise.

In summary, the research expertise includes: instability-related problems (buckling), new metallic materials (stainless steel), numerical simulations of construction processes, time-dependent effects in composite structures, plate girders and the systematic usage of FEM in steel structures design. Researchers work in close collaboration with international institutions, universities and research centers and they participate actively in the development of the Spanish Steel Code (EAE-12) as in the ongoing development of European Standards.

CHARACTERIZATION OF RHS-IPE BEAM-COLUMN JOINTS

M. Lozano, M.A. Serrano, C. López-Colina, F. López-Gayarre
Department of Construction and Manufacturing Engineering. University of Oviedo

One of the main priorities of research when referring to steel structures in the recent years has been the characterization of structural joints. This is due to the great importance of a good knowledge of their resistance and the fact that they behave differently depending on the stiffness of the joint. It is very important to implement the correct stiffness of the joint to carry out a reliable structural analysis. Nevertheless, sometimes, it is not so easy to know the actual stiffness of a joint.

The component method is the most important and widely recognized theoretical approach for the evaluation of the stiffness and resistance properties of a wide range of joint configurations. It has been adopted for steel structures by Eurocode-3 as its main tool for the description of the behaviour of joints between H or I sections. The component method is a powerful tool to determine the performance of the connections in terms of strength and stiffness. It is the framework for many researches based on connections. The difficulty in studying altogether the elements and parameters that condition the connections is the reason for focusing on a part or component.

The structural hollow sections are many times a very good proposal for columns in building structures. However, despite the clear advantages of tubular profiles, joints that involve structural hollow sections (RHS or CHS) have been traditionally excluded from the application of the component method. It is obvious that the possibility of applying the component method to this kind of joints would be a significant advance allowing as well the consideration of semi rigid joints. A global saving would be reached adding to the possibility of using well characterized partially rigid joints, thus saving material that may involve the use of tubular columns.

The present project we are working on, intends to apply the component method to joints involving square (SHS) or rectangular hollow sections (RHS) as tubular columns, due to their multiple economic and material saving advantages. For the beam members a pair of IPE sections will be used due to their excellent behaviour when bending is just in the vertical plane which is a common situation in buildings. The research is presented in a comprehensive way, initiating the process with the characterization of the components that are identified in a RHS column as a part of a symmetrically loaded double-sided beam-to-column joint.

DIAPHRAGM STABILIZATION OF STEEL BUILDINGS IN FIRE

Olli Ilveskoski
HAMK University of Applied Sciences

The objective is to study the literature available on the diaphragm stabilization of steel buildings at elevated temperatures. Bracing used in structural systems generally serve two primary functions. They resist secondary loads on structures (e.g. wind bracing) and increase the strength of individual members by resisting deformation in the weakest direction.

The use of self-supporting sandwich panels as stabilizing elements in normal temperature for single steel members such as beams or columns has been recently researched and Recommendations on the Stabilization of Steel Structures by Sandwich Panels published. The European Recommendations give instructions about diaphragm stabilization and connection forces in normal temperature.

This short survey is made to evaluate the present references dealing the diaphragm stabilization of steel buildings at elevated temperature.

European Union
European Social Fund

LIVING. WORKING. MOVING.

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

The METNET network aims to enhance the development potential and the research and innovation capacities of regional innovation systems and wider communities of Europe. METNET provides an international innovation environment for its members and the possibility to expand their regional innovation networks internationally.

METNET seminars and workshops deal with technical aspects of metal construction as well as issues of concern to industry on management, planning and sustainability of projects.

This book covers papers presented and submitted for the tenth annual METNET seminar in October 2016 held at Universitat Jaume I (UJI), Castellon, Spain. The seminar continued the METNET tradition of presenting scientific and development papers of high calibre.

PRINTED
ISBN 978-951-784-784-1
ISSN 1795-4231
HAMKin julkaisuja 4/2016

ELECTRONIC
ISBN 978-951-784-785-8 (PDF)
ISSN 1795-424X
HAMKin e-julkaisuja 6/2016

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES