5th International Conference
"Computational Mechanics and Virtual Engineering"
COMEC 2013
24- 25 October 2013, Braşov, Romania

# ACTUAL STATUS OF GUSSETED JOINTS OF AEROSPACE WELDED STRUCTURES

G. Dima[1], I. Balcu[2]
[1]Nuarb Aerospace SRL, Brasov, ROMANIA, g.dima@nuarb.ro
[2]Transylvania University, Brasov, ROMANIA, balcu@unitbv.ro

***Abstract:*** *Welded structures are used from early aircraft using a variety of materials, procedures and designs. Paper identify gusseted joins of welded structures in a multidisciplinary approach, including aerospace and civil engineering. Weld gusseted joints of thin walled structures are not standardised and there are no methodology for calculation, existing only design reccomandations. Paper identify the status of different approach of gussets in literature, focusing on the future work to be done in this area.*
***Keywords:*** *aircraft structure, latticed beams, tubular joints, gussets, welded structure*

## 1. GENERAL

Welded structure are first used in aerospace structure for Fokker Eindeker (1915) for the fuselage [L02]. Since than, welded structures passed through a complex process of improvement related to material employed, topology or technological process. Beacuse of problems showed by welding (big dependece of welder skills, poor fatigue behaviour) in time manufacturers searched a lot of alternate designs (especially by riveting) , ending by adoption of welding or semimonocoque structure.

Nowadays weldings are used on aircrafts for structural applications like fuselage (for light aircrafts), landing gear, equipments or external mounts, seats, engine supports, or non-structural applications like brackets, fairings, tanks or inlets

## 2. CLASSIFICATION OF WELDED STRUCTURES ON AIRCRAFT

Heavy loaded structures on aircraft are categorised in primary structure (their failure leads to loose of structure integrity), secondary structure (their failure leads to emergency landing) and tertiary structure (failure allows flight to the first airport).

Welded structures on actual aircraft are used as follows:

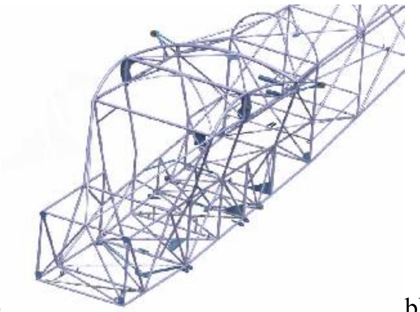
- Primary structures – fuselage (light airplanes and helicopters) (Fig. 1 a), helicopter tail booms;
- Secondary structures – landing gear, ailerons, elevator, rudder (Fig. 1 b)
- Tertiary structure and brackets - engine supports (Fig. 2 a), defence systems, cargo swing (Fig. 2 b);

The aircraft welded structures have in common some specific features as follows:

- Using of CHS (circula hollow structures) for higher overall buckling strength, higher radius of gyration function of cross sectional area and smaller effective buckling length than that of angle profiles [F02].
- Using of inseted bushing and end memers lugs/ forks for external mounts
- Using of gussets to decrease stress leve in joins

There are authors considering circular section similar to nature's optimal response to combined loads as bamboo or bones structure. In [K01] it is shown that, for the same bucling capacity, a CHS column has only 60% of mass of an "I"or "H"profile.

Aerospace structures use CHS (Chircular Hollow Structures) also because of minimum aerodynamic drag, despite geometry of members in connection areas or multiple members nodes. Gussets are employed in structural nodes to improve strength and rigidity.


a)

b)

**Figure 1:** Stol King a) Welded fuselage; b) Empennage

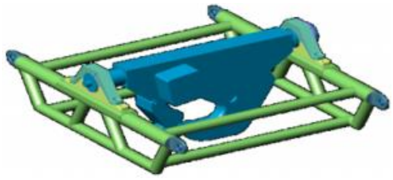

a)

b)

**Figure 2:** a) Engine support; b) Helicopter cargo swing

## 3. WELDING VS. OTHER ASSEMBLY TECHNOLOGIES IN AEROSPACE

In aerospace are used riveting, bolting, bonding and machining (for integral structures). The biggest disadvantage of welding is crack propagation through all the structure, in other built up structures cracks stopping into the affected member. An other problem is related to the structure nodes with more than three members, because welds overlap has to be avoided because of altering the characteristics of previous one.

As technological disadvantages of welding are noted [I01], [N01]:

- The need of positioning and fixture jigs;
- The need of tubes end milling, especially for multiple and non-orthogonal joints;
- Thermal expansion/ contraction of the members during the welding process the deformation of whole assembly because of post weld internal stresses (these problems can be reduced/ eliminated by intercalated welds, welding technology, preheating of welding area;
- Mechanical proprieties changing after welding; [N01]recommends a 10% reduction of allowable stresses for joint calculation;
- Welding flaws, affecting the strength of joint; this leads to high qualified workmanship;
- Expensive non-destructive control methods

As advantages over other assembly techniques [C02] specify:

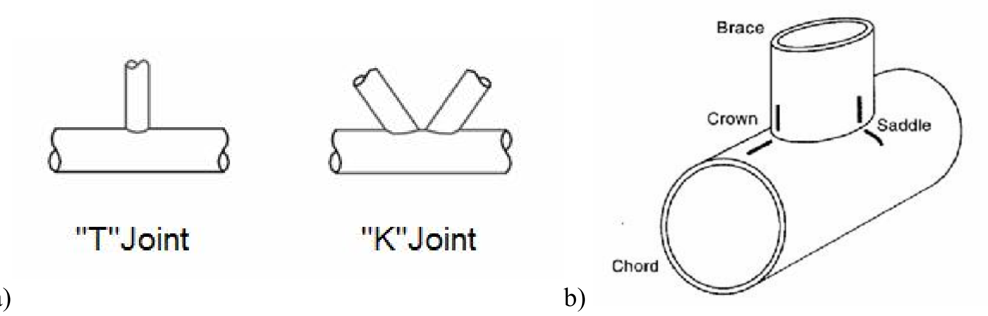
- More rational shapes for subassemblies;
- More effective use of raw material and manufacturing time savings;
- The possibility for automation and manufacturing time reduction;
- Cheap and easy to maintain manufacturing machines;
- The absence of fasteners
- A superior strength for long welds

Recent studies are dedicated to replace riveting and bonding of stringers on the skin by welding. In [Z02] is concluded hot spot stress level is lower the in riveted structures, and the smallest crack growth rate related to machined and riveted structures. The problems of crack propagating through all welded structure remains.

## 4. CHS WELDED JOINTS WITHOUT GUSSETS

CHS (Circular Hollow Structures) are together with RHS (Rectangular Hollow Structures) very used in civil engineering (including offshore platforms and cranes)too, the joints being static, dynamic and fatigue analyzed in[K01], [P01], [W03], [W01] and [Z01].

Literature presents many kind of planar and multiplanar joints between same type of different kind of members (hollow or open profiles). In [*02], [K01] and [W01] there are presented connections between CHS and ”I” or ”U” shape profiles.[K01] shows that the most usual configuration for combined loads is between same kind of members (CHS/ CHS or RHS/ RHS), other combinations being very rare. For aerospace present interest "T" and "K" joints (Fig. 3 a). There are analyzed axial load (AXL), in plane bending (IPB) and out of plane bending (OPB).




a) b)

**Figure 3:** a) "T" and "K" joints[Z01]; b) Terminology of "T" joint [P01]

Fig. 3 b) presents the terminology in the points o of interest of "T" joint. Starting form sixties there were made a lot of studies regarding strength design and fatigue behavior of "T" connection especially from civil engineering area. Most recent accepted results for unstiffen "T" joint are given in [Z01]; there are given values for SCF (Stress Concentration Factor) for:

- AXL – Chord (Saddle & Crown) and Brace Saddle & Crown)
- IPB – Chord (Crown) and Brace (Crown)
- OPB – Chord (Saddle) and Brace (Saddle) (Value for IPB Saddle and OPB Crown are considered negligible)

Last researches in CHS area are oriented to:

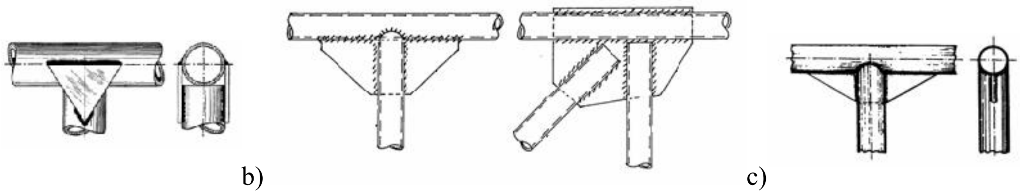
- "T" joint HSS under combined AXL and IPB loads [H01]
- Fatigue behavior of hollow structures [C05]
- Elliptical hollow structures [N01]

## 5. CHS GUSSETED WELDED JOINTS DESIGN

In heavy loaded civil structures, gussets are added to allow bracing connection. [C01] and [K01] present design recommendations related to CHS gussets stress gradient and limit deflection.In civil engineering gussets are also used to connect horizontal beams to columns ("seat brackets"), or connection of columns to basement plates [B01], [*02] and [M01].

[N04], [N05], [P01] presents studies related to the strengthen "T" joint using base plate ("chord doublers") or external collar [B01].[B01] also presents using gussets for stress level lowering in "K" joint; [N04] analyzed economical repair of damaged structures using chord doublers.[N03] made a study related to reducing the stress level in "K" joint by adding gussets (Nazari and Durack) showing the SCF (Stress Concentrator Factor) decrease with 45% for axial loads, 33% for in plane bending and 18% for out of plane bending.

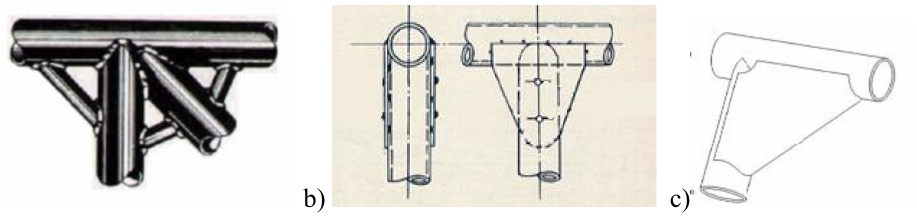
In literature there are given many examples of gussets; the shape, proportion and dimensions vary by author (Fig. 4 and 5). Gussets are radial or tangent placed, inserted in members or not. In nodes with bracing they are used also for bracing connection.



a) b) c)

**Figure 4:**Gusset examples a) triangular [P02]; b) Double [N01], [B04], c) Double [B04]

Between the wars were used connections with tubular gussets used also for wire bracing connection (Fig. 5 a). A particular application is presented in Fig. 5 b), welds in vertical member being made in holes made in gusset. "U" Shaped section gusset (Fig. 5 c) is recommended for roll cage of racing cars. The length of gusset is recommended to be three times bigger than tube diameter [*01].



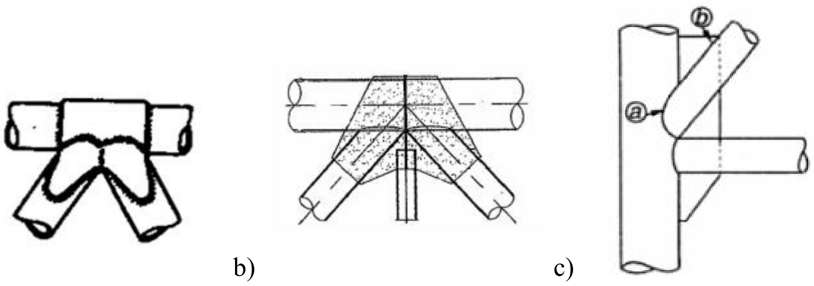
a) b) c)

**Figure 5:** Gusset examples a) Tubular [avia-it.com]; b) Hole welded [G01]; c) "U" Shaped [*01]

According [N07] tapered gussets need to be used in all important joints to provide gradual changes in stress level in joint members; gussets are further recommended for stress level reduction for lowering fatigue effects. [F01] recommends gussets for joints reinforcing, adding strength and rigidity, being also a safety solution. Employing gussets increase also the torsional rigidity of the whole structure. [B04]recommends gussets especially for vibrations and/ or OPB subjected areas. In [B04] there are presented few types of gussets but there are not given any pre-dimensioning or design recommendation.

Related to 'K" joints diversity of gussets is also big. Gussets can be with external doubler (collar ) (Fig. 6 a), inserted in symmetry plane of joint (Fig. 6 b). Ref. [D03] recommends gussets for:

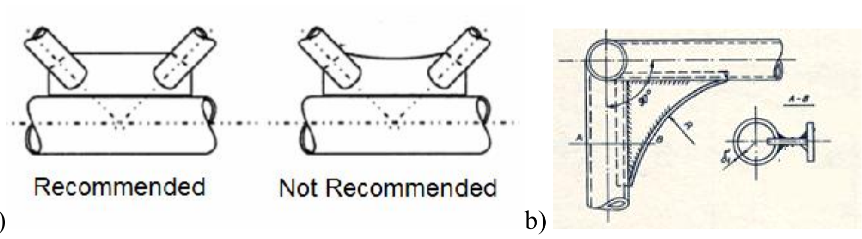
- Additional weld length provided (Fig. 6 c);
- The possibility to shorten the braces (load being carried by gusset)



a) b) c)

**Figure 6:**"K" Joints gussets: a) With collar[I01]; b) Inserted [N03]; c) Weld (a) secured by weld (b) [D03]

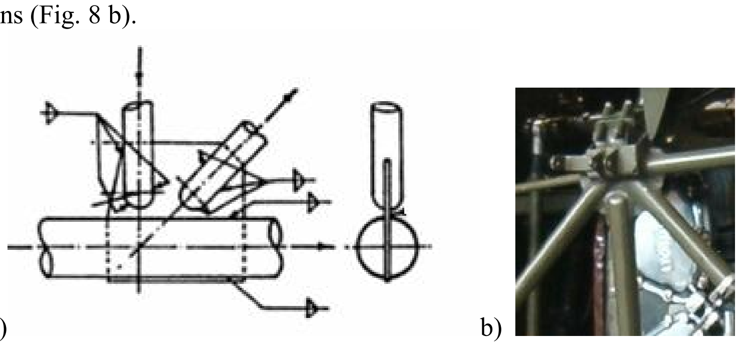
Gusset free margin is recommended to be curved to decrease the stress level in braces (Fig. 7 a) [D03]. Ref. [G01] presents a curved free edge gusset with welded stiffened strip to prevent buckling (Fig. 7 b).




a) b)

**Figure 7:** a) Curved free margin gusset [D03]; b) Flanged free margin gusset [G01];

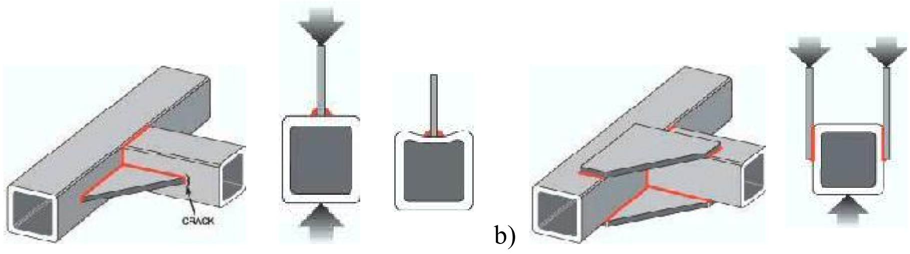
Ref. [P03] recommends ending the members in gusset by spherical forming (Fig. 8 a). This solution is very used in aerospace applications (Fig. 8 b).



a) b)

**Figure 8:** a) End formed braces [P03]; b) Gusseted node - SA315 helicopter [Deutsche Museum, Oberschleissheim];

Related to radial vs. tangent placement of gusset, ref. [B02] mention problems raised by radial assembly as cracks in brace at gusset margins and chord deformation (Fig. 9 a). After [B02], correct placement of gusset is tangent to members of joint, also recommending using carefully gussets because they transfer loads but also add rigidity to joint leading to members failure. Therefore, before adding gussets an analysis of consequences should be made.




a) b)

**Figure 9:** a) Radial placement and b) Tangent placement of gusset [B02];

In practical design, gussets are dimensioned relative to tubes diameter, followed bya verification with a FEM analysis being performed. In lightweight structures, weight savings is related also to the shape of gussets. A correct designed gusset will decrease the stress level in the most stressed area, leading to the need of a lighter tube, thus a lighter structure. It is important to mention the existence of many welded structures free of gussets. This is due to the fact design approach in aerospace in not yet homogenous, depending a lot of the design team of manufacturer.

## 6. CHS GUSSETED WELDED JOINTS DESIGN

Ref. [M04] use for pre-dimensioning the calculated length of welds. Also based on the welds length, in [C02] are presented pre-dimensioning of gusseted joined with braces not in contact with chord and in [N06] and [S01] are presented cutted formed end tubes attached to gusset. [T01] analyzed the stress distribution for double gusseted "T" joint, noting that stress distribution depends a lot function of joint type, its peaks (HSS) having a great influence over fatigue life.

First studies for understanding the behavior of aerospace CHS welded structures was performed by NASA in thirties [B03], being analyzed simple and gusseted tubular joints from different materials, thermal treatment of welding process. The study was focused on "T" and "K" joints, AXL and IPB loaded, all results being associated with weight savings. It was found that inserted gusset joints had best results, performances being improved by gusset cutout in member joining area.

Ref. [H02] give an example of stress value and location and critical buckling stress calculation for a thick rib (Fig 10).

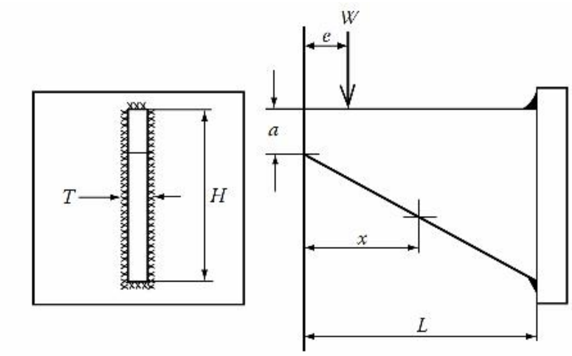



**Figure 10:** Trapezoidal plate plane loaded parameters [H02];

Recent studies related to gussets are focused on:

- Gusset to strap connection under axial load [J01];
- Fatigue behaviour of OPB loaded gussets [K02];
- Failure of tube gusset connection under AXL loading [C03], [M02], [M03], [L03], [K01], [M05] and compression [L01];
- Buckling of gussted to open profiles bracing connection [C04], [C06], [R01], [N02]
- Plane end tube to gusset connection [O02]
- Parabolic free edge gusset stress distribution [S02]

## 7. CONCLUSIONS

CHS structures are present in many applications on aircraft structures, but dedicated studies for joints are more close to the steel construction area. It can be concluded that:

- Despite of the big variety of gussets for joints (number of gussets, form, section, free edge shape, dimensions, proportions, radial or tangent placement, inserted or not in joint members) there are no design recommendations for gussets form and placement function of load type or application;
- There are no design recommendations where to use or not gussets for joints reinforcement;
- There are no studies to asses gusseted joint vs. simple braced joint;
- There are not recommendations regarding pre-dimensioning or stress calculation of gussets (plane dimension and wall thickness);
- Existing studies for non stiffened joints are for civil engineering range (general over 100mm diameter), for aerospace thin wall tube structures (diameters in range 16 – 40mm) information being not available;

## REFERENCES


[B01] Blodgett O. W., Design of Steel Structures, The James F. Lincoln Arc Welding Foundation, 1976

[B02] Blodgett O. W., Using gussets and other stiffeners correctly, www.weldingdesign.com, 2005

[B03] Brueggeman W., Strength of Aircraft Joints, NACA Report No. 584, 1936

[B04] Bruhn E. F., Analysis and design of flight vehicle structures, Tri-State Offset Company, 1973

[C01] Cao J. J., et al., Design Guidelines for Longitudinal Plate to HSS Connections, Journal of Structural Engineering, 1998

[C02] Constantin E. T., Proiectarea masinilor, utilajelor şi construcțiilor sudate, Suport de curs, Universitatea din Galați, 1981

[C03] Cheng J. J., Kulak G. L., Gusset Plate Connection to Round HSS Tension Member, Engineering Journal, Fourth Quarter, 2000

[C04] Chou C. C., Chen P. J., Compressive behaviour of central gusset plate connections for a buckling-restrained braced frame, Journal of Constructional Steel Research, No. 65, 2009

[C05] Conti F., Verney L., Bignonnet A., Fatigue assessment of tubular welded connections with the structural stress approach, Fatigue Design Proceedings, Senslis France, 2009

[C06] Chou C. C., Liou G. S., Yu J. C., Compressive behaviour of dual gusset-plate connections for buckling-restrained braced frames, Journal of Constructional Steel Research, No. 76, 2011

[D03] Duggal S. K., Design of Steel Structures, Tata McGraw Hill, New Delhi, 2009

[F01] Fournier R., Fournier S., Metal Fabricator's Handbook, Penguin, 1990

[F02] Farkas J., Jarmai K., Analysis and Optimal Design of Metal Structures, Balkema, Rotterdam, 1997

[G01] Grosu I., Calculul şi construcția avionului, Editura didactică şi pedagogică, Bucureşti, 1965

[H01] Haghpanahi M., Pirali H., HSS Determination for a Tubular T- Joint under Combined Axial and Bending Loading, Internațional Journal of Engineering Science, Vol 17, No 3-4, 2006

[H02] Huston R., Josephs H., Practical Stress Analisys in Engineering Design, CRC Press, 2009

[I01] Iliescu P., Mitu P., Stoian G., Manualul tinichigiului structurist de aviație, Ed Didactică şi Pedagogică, Bucureşti, 1974

[J01] Jensen A. P., Limit analysis of gusset plates în steel single-member welded connections, Journal of Constructional Steel Research, Nr. 62, 2006

[K01] Kiymaz G., Seckin E., Investigation of the behaviour of gusset plate welded slotted stainless stell tubular members under axial tension, 14th Internațional Symposium on Tubular Structures Proceedings, London, 2012

[K02] Kishiki] S., Yamada S., Wada A., Experimental evaluation of structural behaviour of gusset plate connection în BRB frame system, The 14th World Conference on Earthquake Engineering, China, 2008

[K03] Kurobane Y., et al., Design guide for structural hollow section column connections – CIDECT/ TUV Verlag, 2004

[L01] Lee H. D., et al, Investigation of the Tube-gusset Connection în 600MPA Circular Hollow Section, Procedia Engineering, Nr. 14, 2011

[L02] Loftin L. K., Quest for performance. Evolution of modern aircraft, NASA Scientific and Technical Infromation Branch, Washington, D.C., 1998

[L03] Ling T.W., et al, Investigation of block shear tear-out failure în gusset-plate welded connections în structural steel hollow sections and very high strength tubes, Engineering Structures, Nr. 29, 2007

[M01 Martin L. H., Purkiss J. A., Structural Design of Steelwork, Butterworth-Heinemann, 2008

[M02] Martinez-Saucedo G., Packer J. A., Slotted end connections to hollow sections, CIDECT Report 8G-10, 2006

[M03] Martinez-Saucedo G., Packer J. A., Willibad S., Parametric finite element study of stotted end

connections to circular hollow sections, Engineering Structures, Nr. 28, 2006
[M04] Mateescu D, Caraba I., Construcțiimetalice. Calcululşiproiectareaelementelor din oțel, Edituratehnică, Bucureşti, 1980
[M05] Moreau, R., Finite element evaluation of the “modified-hidden gap” HSS slotted tube-to-plate connection, Connections VII, 7th Internațional Workshop on Connections în Steel Structures, Timişoara, 2012
[N01] Narayna K. S., et al, Static strength analysis of elliptical chord tubular T-joints using FEA, Internațional Journal of Multidisciplinary Educațional Research, Vol1, Issue 4, 2012
[N02] Nascimbene R., Rassati G. A., Wijesundara, K., Numerical simulation of gusset plate connections with rectangular hollow section shape brace under quasi-static cyclic loading, Journal of Constructional Steel Research, 2011
[N03] Nazari A, Durack J., Application of The HSS Method to The Fatigue Assessment of HSS Shiploader Boom Connection, 5th Australasian Congress on Applied Mechanics, Brisbane, 2007
[N04] Nazari A., et al., Analytical Methods for Better Design and Repair of Mechanical Welded Structures, CRC Mining Technology Conference, Fremantle, 2003
[N05] Nazari A., et al., HSS Design with parameters equations for fatigue assessment of tubular welded structure, Australian Mining Technology Conference, 2006
[N06] Novac Gh., Proiectarea masinulor, utilajelor şi construcțiilor sudate, Suport de curs, Universitatea Transilvania Braşov, 1991
[N07] Niccoli, R. History of Flight, White Star, Italy, 2002
[O01] Ocel J. M., Dexter R. J., Fatigue-Resistant Design for Overhead Signs, Mast Arms Signal poles and Lighting Standard, Minnesota Department of Transportation, USA, 2006
[O02] Oliveira C., Christopoulos C., Packer J. A., High Strength Brace Connectors for use în SCBF and OCBF, SEAOC Convention Proceedings, 2011
[P01] Packer J. A., Henderson J. E., Hollow Structural Section – Connections and trusses - Canadian Institute of Steel Corporation, 1997
[P02] Parmley R., Illustrated Sourcebook of Mechanical Components, McGraw Hill, 2000
[P03] Punmia B. C., Ashok K. J., Arun K. J., Comprehensive Design of Steel Structures, Laxmi Publications Pvt Ltd, 1998
[R01] Roeder C. W., Lompkin E. J., Lehman D. E., A balanced design procedure for special concentrically braced frame connections, Journal of Constructional Steel Researchm Nr. 67, 2011
[S01] Şerb A., Proiectarea şi încercarea structurilor sudate, EdituraTehnică – Info, Chişinău, 2001
[S02] Syed Z. I., Stress analysis of welded gusseted frames, Iowa State University, 2011
[T01] Teodorescu C. C., Mocanu D. R., Buga M., Imnibarisudate, Edituratehnică, Bucureşti, 1972
[W01] Wardenier J., et al., Hollow Sections în Structural Applications, CIDECT, 2010
[Z01] Zhao X. J., et al., Design guide for circular and rectangular hollow section welded joints under fatigue loading, CIDECT/ TUV Verlag, 2001
[Z02] Zhang X., Li Y., Damage Tolerance and Fail Safety of Welded Aircraft Wing Panels, AIAA Journal, Vol. 43, No. 7, 2005
[*01] * * *, Roll Cage Construction, Appendix B, nasa Rally Sport, 2011, nasarallysport.com
[*02] * * *, Eurocode 3, Part 1.8. Design of Joints, CEN, 2002