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NOTES ON EVOLUTION OF AIRCRAFT STRUCTURES LATTICED BEAM JOINTS

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Abstract: *Latticed beams are met in aerospace structures from the beginnings of aircraft, being used a big variety of materials, configurations and joints. Paper presents representative solutions used on primary structure from the first aircrafts to the moment semimonocoque structures became a standard. It is shown the evolution of latticed beam joints was not a linear and smooth process, an analysis of factors influencing and possible explanations being stated.*
Keywords: *aircraft structure, latticed beams, tubular joints, gussets, welded structure*

1. GENERAL

The latticed beam was the first structure to offer aviation manufacturers an acceptable compromise between strength, rigidity and internal storage volume for a minimum weight. Latticed beam is the most enduring structure for aircraft, being still used on light aircrafts.

One of the characteristics of aircraft beams is the complexity of structural joints. Due to the swept aerodynamic form, the internal structure needs to offer support to a complex shape. Thus, the rectangular or prismatic frames used in the beginnings of aircraft era, were replaced by trapezoidal or irregular polygon (especially for helicopters).

Replacement of wire bracing (stay wires) with diagonal members leads to triangular stiffened beams in all planes but also to very complex members connections. In main fuselage attachment points (hard points for wing, empennage, landing gear) structural joints were stiffened to withstand the concentrated loads.

A big variety in joint design can be seen depending on manufacturer, even on aircraft; it was a lack of design homogeneity or standardisation.

2. THE BEGINNINGS

Since the beginnings of aircraft history, a lightweight structure strength was one of biggest challenge for pioneers together with the aerodynamic of lifting surfaces, an appropriate thrust source and accurate controls. The first controlled successful flight was not only an fortunately attempt, being the result of a scientific approach of Wright brothers, based on a carefully study of the research of their forerunners like Sir George Cayley, Otto Lilienthal or Octave Chanute [02], [08]. Being the author of an well-known monography, Octave Chanute, an successful civil engineer (bridges and railroads) acted as consultant for Wright brothers. It was Chanute's idea to combine the biplane (intensively tested by Lilienthal) with the latticed beam, resulting a high inertia momentum beam [04].

Figure 1 (a) presents Lilienthal bird like wing biplane with upper plane mounted on a mast; having wooden ribs, the margins of the wing were wire attached by mast. In Fig. 1 b) Wright's Flyer had the two wings of the biplane acting as two flanges of a Pratt beam; having three bays each side, those were reinforced with diagonal wire bracing, this being a lightweight innovation in order to replace the diagonal bracing [14].

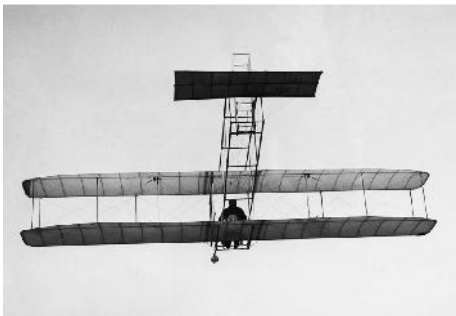
a)  b) 

Figure 1: a) Lilienthal biplane [Deutsche Museum, Oberschelissheim]; b) Wright's brothers Flyer [12]

The difference between Fig. 1 a) and b) is obvious, only after seven years Flyer having a minimum weight and also stiff enough to support the aerodynamic loads. The Wright brothers concept was a great leap forward, in a period when the design was "chaotic" [11] and up to 1912 to the biggest majority of prototypes ("strange machines") the fact they will take off was like gambling [11], or "cut & try" method [09]. Being a compromise between many conflicting requirements, therefore hard to be obtained, even nowadays, the design of a successful aircraft is not an exact science [07].

3. LATTICED BEAM OF EARLY AIRCRAFTS

Latticed beams of early aircrafts were composed by longerons, columns and diagonal members (wire bracings). The most used section was square but there were also exceptions (Fig . 2). The longerons were initially made from ash or hickory, spruce being used later for weight saving [03].

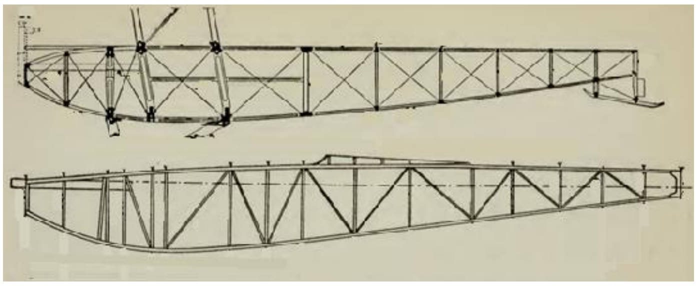
a)  b) 

Figure 2: a) Vollmoeller plane with triangular fuselage section [Deutsche Museum, Oberschleissheim]; b) Side view of wire braced (Spad 13) and diagonal members fuselages (Hansa Brandemburg) [10]

Wire bracing even having low weight, needed a skilled mechanic to adjust and maintain them, having the risk of structure failure if one wire fails. For theese reasons, manufactures tend to replace wires with diagonal members, leading also to simplified structure joints (Fig. 2 b).

Camm in 1919 noted that the design and type of fittings employed for connecting the latticed beam members varies greatly, being one of the distinctive constructional details of a plane, being mainly the result of desire for originality of each individual designer and had to disappear with the progress of the industry [03]. Even this aspect leads to manufacturing and productivity problems, it was propagated until nowadays.

In the early days of aviation, the fuselage fittings were made of aluminium alloy, but after in 1915 the standard fittings were from stamped steel [10]. Figure 3 shows different types of systems: "U"shaped bolts - Bleriot (a), aluminium sockets – Deperdussin (b), stamped and bent sheets with welded sockets – German Aviatik (c). The fittings were provided with eyelets for wire attachments.

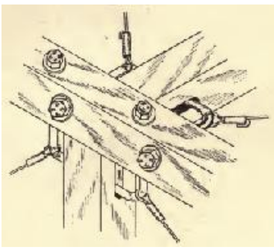
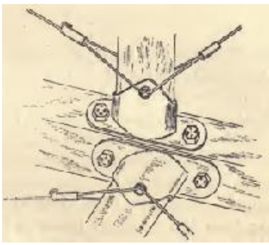
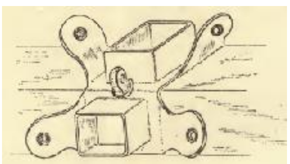
a)  b)  c) 

Figure 3: Latticed beam fittings: a) Bleriot; b) Aluminium Socket; c) Stamped and welded [03]

Because of problems related to wooden/ fabric construction, manufacturers searched for solutions to eliminate the lack of durability, crashworthy and damage tolerance, flammability, anisotropy, wire bracing and so on. Between latticed beams and semimonocoque, there were a lot of concepts as:

- Beam without diagonals, with external stiffening skin;
- Beam with longerons, frames column members replaced by frames with stiffening skin;
- Beam with a system of stringers replacing the longerons, reinforced by circular soft frames and swept skin;
- Beams with frames, diagonal wire bracing and skin

As materials there were employed:

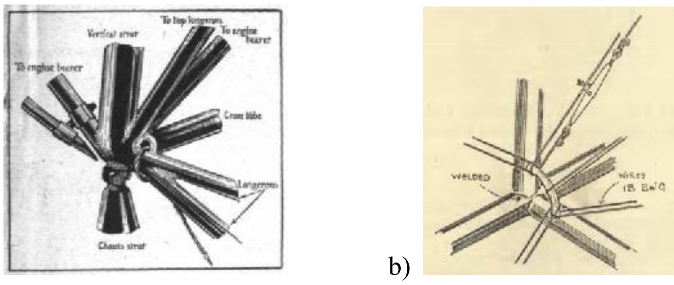
- Wood, aluminium or steel tubes for longerons, columns, frames and diagonal members
- Plywood, veneer, steel or aluminium sheet metal (plain or corrugated) for skin and frames
- Aluminium or steel for connections and fittings

It can be concluded a big mixture of members type and materials was used; in a logical approach these concepts leads to the semimonocoque, but many of this solutions were used many years after successful semimonocoque plane. Even semimonocoque appeared in 1912 (Deperdussin) showing improved features and characteristics, because of manufacturing costs it was not implemented in the design of the new aircrafts of the era. One of the biggest requirement of the First World War was the short development time, as a response to battlefield request. There were aircrafts which were released only after 3 – 4 months after first hand sketches [07].

The transition from bamboo and wood to metal led to the requirement of new joining techniques. Starting from 1907, Anthony Fokker used on his airplanes welded structure, joining up to eight members also with hinged struts and wires (Fig.4 a).

Since 1919, Camm stated that metal tubing is the most practical form in which steel can be used on aircrafts [03]. In Fig. 4 b) is presented a joint with gusset like curved tublets for wire connections. There were used also spruce filled tubes to prevent local buckling [03].

Welded tubes structures were known and appreciated for accuracy and productivity since First World War, but welding techniques needed more progress in order to compete with wooden structures. Flight magazine noted in 1918, that Fokker structure welded nodes are the result of an “excellent workmanship”. Early problems with welding led to the idea the welding depends a lot of the welder skills, this being propagated until present time.



a) b)

Figure 4: Welded joints on early planes: a) Fokker joint [Flight, Oct 1918]; b) Camm joint [03]

Manufacturing drawbacks due to the lack of knowledge added to welds fatigue failure determined producers to find alternate solutions as bracket or riveted joints..

4. NON-WELDED LATTICED BEAM

Riveted sheet metal structures got in to aviation very early, being employed by engineers working in Zeppelin team. Having the experience of huge airships structures, they come with the experience of lightweight latticed beams, with lightweight details. Aplying this first to flying boats (the biggest ariplanes of that time), the structural members were hollow structures or latticed beams, leading to higly complex structural nodes (Fig. 5).

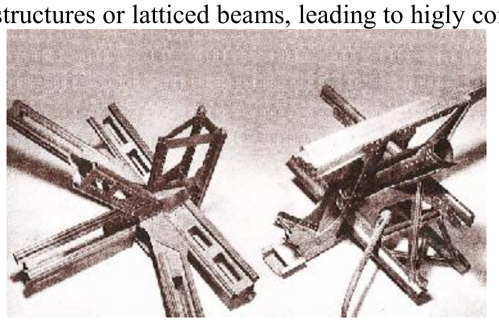
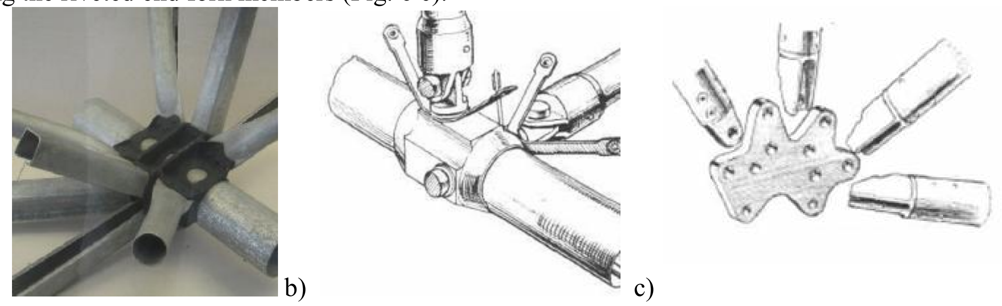


Figure 5: Hollow sections members riveted nodes of Dornier Rs.I flying boat (1915) [13]

After J1 unsuccessful attempt to use metallic welded stressed skins, Junkers concentrated himself on multiplanar latticed structures. These structures needed dedicated nodes, Junkers using as members closed and also open profiles (rarely used in aerospace) with formed ends. The joint was secured by formed steel brackets riveted together with members ends (Fig. 6 a).

Other designs used machined tube end fittings welded or riveted on members. Welded was replaced because circular welds were not stiff enough (welds have to be used in order to allow shear and avoid tensile loading). Figure 6 b) shows an example with tubes connected to lugs with threaded shaft. Other example is a planar bracket joining the riveted end fork members (Fig. 6 c).

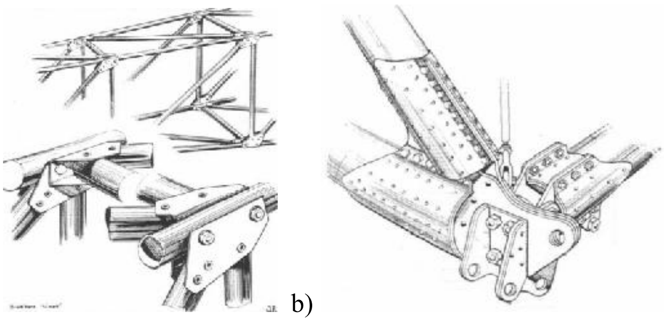


a) b) c)

Figure 6: a) Formed joint brackets (Junkers, 1924) [Deutsche Museum, Oberschleissheim];
b) Machined ends tubes joint (Sidestrand, 1926) [Flight, Jul 1929];
c) End forks riveted tube joint [Flight, May 1930]

In 1928 Blackburn Lincock used a hibrid solution by riveting sheet metal brackets to the end of beam members. Brackets were attached by tubular rivets which in time had not satisfactory results; in present this kind of rivets are not used in structural applications (Fig. 7 a). Planar columns and diagonals subassemblies were riveted, while they were screw mounted on longerons.

Short find a different solution to provide a smooth tension flow from structure attaching points to the beam members by inserting gussets in splitted end of members. The connection between members and gussets was made by the meaning of twin doublers riveted to members with blind rivets (Fig. 7 b). Even this concept is very robust and insure a long service life, it employs a big number of workmanship to every joint. In present time blind rivets are not allowed for structural applications.

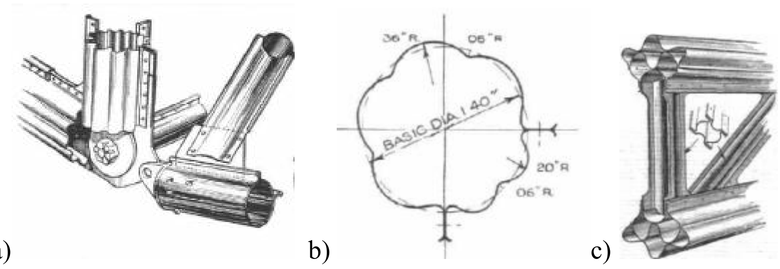


a) b)

Figure 7: a) End brackets riveted to members (Blackburn, 1928) [Flight, Jul 1928];
b) Members with riveted end doubler and gussets (Shorts Valletta, 1930) [Flight, Jul 1930]

Lightweight structures employ thin walled structures, thus buckling being one of the biggest problem. To prevent buckling, Bristol used in 1929 corrugated sheet members. In Flight magasine (1929) is mentioned that corrugated sheet columns had a better buckling behaviour than circular section tubes (Fig. 8 a). Making an assesment study, the conclusions are:

- For the same wall thickness and critical general buckling force, the corrugated sheet column weight is 40% bigger than circular section tube. The local buckling critical force is 90% of the circular section tube.
- For the same mass and wall thickness, the general buckling critical force of the corrugated sheet column is 35% lower than the circular section tube. The general local buckling force is 90% form the circular section tube.
- The corrugated columns do not save weight and do not improve buckling behaviour by geometry; the single improvement can be acomplish by local hardening obtained by small bend radius of corrugations.



a) b) c)

Figure 8: Corrugated sheet members with gussets (Bristol 110A, 1929) [Flight, Jul 1929];
b) Corrugated member section [Flight, Feb 1928]; Corrugated sheet longeron (Stal 2) [Flight, Nov 1934]

In the thirties spot welding start to be used in aerospace; in Fig. 8 c) is given an example from Stal 2 plane – a very complex and expensive solution. Currently the spot welding has very limited applications on aircraft primary structures.

In 1934 Shorts used riveted profiles columns to improve buckling behaviour. Gussets were used not only to join the members, being bigger than joint dimensions. Solution were similar with metallic bridges (Fig. 9). Riveted profiled members were used for many aircrafts, as usual for longerons or high loaded stringers. For closed section members (hollow structures) currently are used omega and "U" profiles.

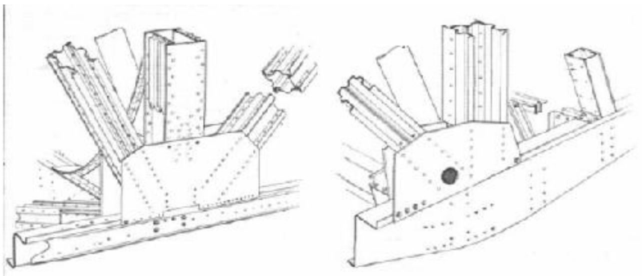


Figure 9: Riveted profiles columns with gussets (Scylla, 1934) [Flight, Apr 1934]

In 1928 Flight presents a simplified structure with gussets junctions to every node (Fig. 10). Gussets were inserted in the symmetry plane of members manufactured from two or three omega profiles riveted. Even presents a big number of rivets and the weight is increased by the flanges of the members, the structure is simpler than the structures used before, having also a better shock behaviour (in hard landing). Gussets help also to decrease the buckling length; a 20% reduction of buckling length leads to 50% increase of buckling force.

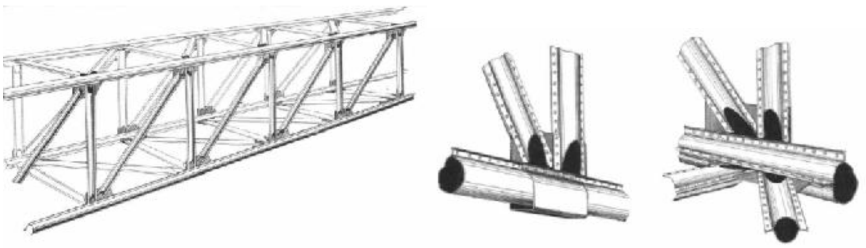


Figure 10: Latticed beam and joints of riveted omega profiles members [Flight/ Aircraft Engineer, Feb 1928]

A late application of brackets mounted latticed beam is met on Hawker Hurricane (1935). Using steel longerons and aluminium columns and bracing, it employed steel brackets both bolted and riveted to beam members. Fig. 11 shows the fuselage and centre structure beam and few details of nodes with different geometry or concept leading to a big development effort.

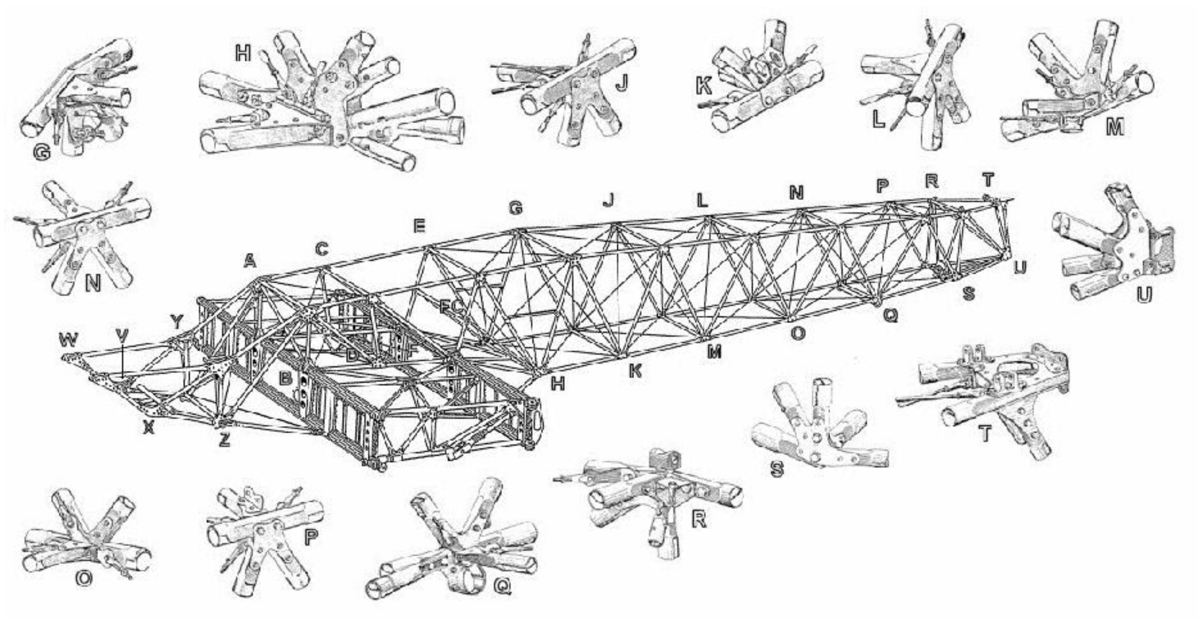
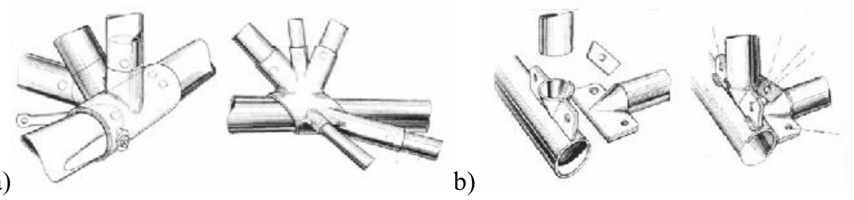


Figure 11: Central structure and fuselage (Hawker Hurricane, 1935) [militaryphotos.net]

5. WELDED LATTICED BEAM

Parallel with developing riveted or bolted concepts, progresses were made with welded joints. Intermediate concepts are shown in Fig. 12 a) and b) with doublers and gussets inserted in members end. Doubler and local stiffening plates are used also in civil engineering; in aircraft remained only members direct welded to each others, employing or not gussets.



a) b)

Figure 12: a) Doubler joints; b) Members inserted gussets joints [Flight, May 1929]

In 1930 Avro Trainer presented more new solutions which being kept and developed in time as follows:

- Bushing inserted in tubes for external members bolted attachments (Fig. 13 a);
- Formed end tubes for joining smaller diameters tuber (Fig. 13 b);
- Tangent placed gussets used also for external fittings attachement (Fig. 13 c, d)
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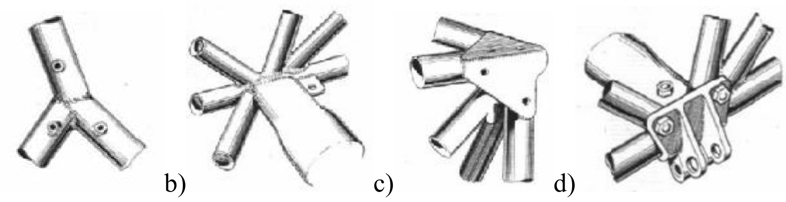

a) b) c) d)

Figure 13: a) Tubes inserted bushing; b) Joined formed end tube;
c) Gusset as basement for fitting; d) Fitting attached to welded gusset [Flight, 1930]

Even in time there were a lot of alternative to welded joints for latticed beams, currently is used only welding for tubular structures.

Welded fuselage is not employed on airplanes from 40's, being extensive used for helicopters center and tail boon structures up to 70's. For primary structures, latticed beam is used nowadays only for small aircraft fuselage, the wings being made of riveted aluminium structure.

6. CONCLUSIONS

The first reliable structure for aircraft was the latticed beam, solution inspired from civil engineering. Used for fuselage and wing, it was a standard up to thirties, until semimonocoque (originated from ships engineering) [05], [01] finally demonstrated its superiority. Biplane wing was used until monoplane demonstrates its aerodynamic superiority and its internal structure riched a level where the beam made by two planes was no needed anymore.

Latticed beams were made by wooden members with wire bracing until steel or aluminum tubes replaced them, needing a more simple joining. The transition from latticed beam fuselage to semimonocoque was somehow superposed over the transition form wood to metal, but they were almost independent processes even they interfered a lot [06].

Welding is used from the early aircraft but in that time the technology was not mature. For this reason, for more than 30 years manufactures searched for alternative to welding, joining type leading even to members different construction.

Latticed beams are used only in limited application for fuselage, having welded nodes. Weld is used in many other application on aircrafts but not in latticed beam structures (landing gears, empennage, seats, etc).

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