HOT DRIVEN RIVETS – ESSENTIAL BOND FOR IRON PLATES (1780-1920)

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ABSTRACT

The essential role of hot-driven rivets is described for the industrial revolution with very limited-size rolling capability, with costly poor-quality bolts and without dependable fusion welding. While cold rivets were common for ages, the shrinkage of hot rivets gave water or steam tight joint. Rolled plate was limited to 1 x 3 m because of small mills, low power and manual handling. The essentials of riveting procedures and their limitations are described. The application of rivets in boilers, ships and bridges are described.

1. INTRODUCTION

Rivets have been used since the early ages of metals; usually one to three were used to join one piece of metal to another (cast and wrought, bronze and copper). In machinery, they attached small iron reinforcements or wear surfaces to large wooden parts [1-3]; all these were applied by cold hammering to prevent charring and enlarging the holes. The new age of rivets developed only when wrought iron (WI) became available in quantity and at low cost after the introduction of the puddling process after 1780 [1-3]. With the possibility of making machines and structures out of WI, mechanical engineering was essentially born [4]. As an example, M. Fairbairn, who trained as a millwright mainly on wood, developed into a mechanical engineer who conceived, designed and initially hand built machines in iron, including an entire steamboat [5,6]. All wrought iron semi-finished products were hot pressure forged from small puddled bars (15 x 30 x200 cm), which generally required high reductions near 1100°C [1,7-9]. One significant hot forged product was chain links, small to very large, from wires or bars. Another was a longitudinally pressure-welded tube from drawing red-hot, (3.2 or 6.4 m) long skelp (strip with beveled edges), through a die with internal circumference slightly smaller than skelp width [8,10].

While WI was valued because its ductility and toughness were very much higher than those of cast iron, the strengths and hardness were similar except for remarkably hard, white cast iron as established by Réaumur (1722) [1,7-9,11-13]. Steel, available in small quantities and ill defined carbon content or heat treatment, could exhibit strengths similar to WI and cast iron (or much higher), ductilities similar to WI (or much lower) and hardness anywhere between WI and white cast iron. With the perfection of Bessemer and Siemens-Martin processes, steel appeared in quantity after 1860 [2,3,7-9,12]; however, it required another 60 years to clarify the basic science of steel heat treatment [13]. In this period of momentous materials development, Canadian activity in production lagged considerably behind application until about 1916 [1,13].

Because the hot mechanical forming of steel was very similar to WI, the change over to steel in manufacturing and application (machines, boilers, ships, bridges) proceeded almost to completion by about 1910 [12,13]. However, to gain the full benefit of steel over WI in design, the mechanical properties of both had to be determined accurately, requiring clear definition of properties, accurate measurements and building of testing machines; these were magnificently accomplished about 1860 by the new engineers, such as M. Fairbairn and D. Kirkaldy, in Britain [5,6,13,14]. Hot riveting became even more significant for bonding of steel in structures, such as boilers, ships, bridges and skyscrapers; for the last two, mechanical engineers ran the fabrication shops. However, as bolt production was perfected and standardized, 1850-1870 [4-6], they became significant in machinery partly because they permitted disassembly for repairs.

2. BOILERS FOR MOBILE STEAM ENGINES

With the introduction of steam power, a significant component requiring development was the boiler that initially consisted of a large horizontal cylinder that was closed at the ends and was 75% full of water. Inside it and completely submerged in the water, the horizontal fire chamber with a coal grate at mid-level, extended from the stoking door to the smoke stack [6]. Since the walls and rivets were subjected to the direct flame, the water level had to be maintained above it. Cast iron was too bulky, heavy and fragile; wrought iron sheet that could withstand the fire and the pressure and conduct heat was ideal, especially for railroad engines, but small plates had to be patched into pressure tight containers. Rivets were fire proof and could produce watertight joints. Generally, the rivets did not fail but the plate between them bulged or ruptured due to creep. For fixed boiler diameter, a simple improved design by Fairbairn [6] was a double fire chamber with same total volume and burning capacity. This has resulted in larger surface to transmit heat, increased stability from fewer seams and improved coolant security from a greater volume of water above them (a step towards fire tube boilers with pressure welded tubes [10]).

3. HOT DRIVEN RIVETS

The driving of red-hot rivets is much easier than driving them cold, where strain hardening would make it harder and harder to reach the desired tightness (Table 1). The red-hot iron rivets near 900˚C are in the ferritic condition, where they have good ductility and develop a strengthening substructure as they are pounded tight. As they cool, they shrink (~0.9%) clinching the two pieces of metal together; the stresses in the rivet shank attain the yield stress as the temperature descends. More closely spaced rivets and more rows raise the average clamping pressure (Figure 1) [1,16-18]. W. Fairbairn [5,6] conducted experiments to define the optimum spacing and number of rows of rivets, while 2 rows were essential, 3 rows were only slightly better than 2 (Table 2). Since the rivet holes are stress raisers, the spacing should be four times the diameter to diminish that effect. Moreover, riveted joints associated with a metallic discontinuity are very good as crack arrestors compared to welded joints where metal is continuous; moreover, welds may have defects, such as cavities or shrinkage cracks that initiate failure [19]. Rivets were generally used right through World War II when welding was greatly improved.

The rivets, 2.5 to 5 cm diameter, are generally made from hot rolled bar by cold heading (Table 3). They must be heated in a portable forge to a cherry red (900-1000˚C); too excessive a temperature (>1400˚C) or too long a time can cause oxidation or melting at the grain boundaries. The hot rivet is placed in a hole towards the most accessible side and is held by a maul with a head cup (or a 12-lb. hammer) [1,12,16]. On the other side, it is struck repeated blows alternately by 2 hand riveters wielding 9-lb. hammers (Table 4) or by a pneumatic gun with a suitable cup. In the factory, riveting is frequently done by hydraulic rams in a C-shaped frame transported by a crane. Beforehand, the plates, angles, I beams or H beams must have holes the correct diameter (clearance for shank) punched or drilled in the designed locations, so that all parts are exactly aligned (Figure 3) [17].

Steel rivets are likely heated into the austenite range, so suffer an expansion on reverting to ferrite. However, this occurs from contact with the plates and the holding and hammering tools. The transformation to ferrite and to pearlite occurs before driving is complete, so they exert a similar clinching effect as iron rivets but with higher possible stress because of higher yield stress [12,16]. There are two grades of rivets, as shown in Figure 2; the stronger one has ~0.25%C-1.5%Mn compared to 0.19%C-0.5%Mn in the standard [16]. In a properly designed joint the total clinching force should exceed the permissible design strength of the steel, so that the joint remains rigid causing the parts to act as if a continuous member. Rivets that transform slowly to pearlite can attain strengths only a fraction of quench and tempered alloy steel bolts. While rivets served very well for almost two centuries, high tensile bolts have replaced them particularly in the field, since they require no portable forge [16,19]. By means of wrenches with measurable torque, it is also possible to obtain a more uniform clinching force; such bolting technology requires only one worker.

4. SHIP HULLS - PLATES AND RIBS

Iron ship hulls were initially constructed by nailing or cold riveting overlapping iron sheets to wooden hulls. When ship builders became convinced that iron hulls would float without scarce wood, plates were cut and shaped and angles formed from slit plate, were bent to needed contours. Along the length of lap seams or attachments to ribs, at least two rows of rivets were essential. Moreover, with hot driven rivets, the ship hulls were watertight which avoided caulking, as for wooden ships [56]. By modern standards, the pieces of plate seem very small, but they were larger than planks and suitable for hand positioning. R. Roberts, [4], invented a press that could punch groups of holes in identical positions in similar sheets.

The riveted plate and rib technology reached its zenith in ocean liners such as the tragic Titanic and the successful Queen Mary and Queen Elizabeth, as well as the battleships of WWII. Repair of accident or war-damaged ships was achieved by chiseling off rivets and fitting plates, with the holes properly punched. However, the greatest achievement of the plate and rib technology was possibly the Forth Bridge constructed in 1890 as two cantilevers (each 204 + 540 + 204 m, see Quebec Bridge below): all the major members were circular and were shaped, punched and riveted on the site, thus employing about 4000 experienced ship builders [17,19].

5. BRIDGE EVOLUTION; RIVETING CHALLENGE

For long spans (>100m), suspension bridges with W1 chains proved suitable for carriage roads, e.g., Telford's 174m Menai Bridge, utilizing chains of multiple eye bars with pinned connections [21-24]. However, they proved unsuitable for swaying multi-carriage trains that shook the insufficiently stiff truss decks to pieces. For the Menai railroad bridge with 2 spans of 138m (+2 x 69m), R. Stephenson and W. Fairbairn conceived of an elliptical box girder, composed of two ship hulls, one inverted [1,22,24,26]. From extensive large scale testing, buckling in upper compression regions proved worse than potential fatigue in bottom tension regions; both could be easily prevented with a rectangular tube, reinforced top and bottom by a row of six square tubes (the 10% increase in weight more than doubled the load bearing capacity) [12,24,26]. This design was so successful that it gave birth to beam theory and eventually provided satisfactory service for much heavier trains [1,24-26]. In both the Menai Brittania Bridege and the St. Lawrence Victoria Bridge (25 spans, 75-100m) [1,26,27]; the box girder bridges in England and Canada were the first applications of riveting in bridge technology [12,24].

In the early 19th Century in North America, timber truss bridges commonly relied on wrought iron bolts to hold them together and sometimes long iron rods for additional strengthening. However, the heavy vibrating loads tended to enlarge the bolt holes and the uneven loading could splinter the timber; there were several collapses and many more emergency repairs [22]. There were many experiments to combine cast iron compression components with wrought iron tension rods, but these did not prove satisfactory [22]. The solution combined newly developed structural design and fabrication of compression members from wrought iron plates and angles with sound rivet technology. Three wrought iron truss bridges were built and served without incident: on the Inter-Colonial Railroad (Halifax to Montreal) at Trois Pistoles, QC (1870) [1] and over the Miramichi (1872) [28] and on the CPR line at LaSalle, near Montreal [29].

The Victoria Bridge that, as a box girder tube, provided the first railroad crossing [1,27] was rebuilt as a steel Pratt truss of twice the weight, but four times the capacity, carrying a double track and the first road crossing of the St. Lawrence River [29-31]. Bessemer Steel was about 50% stronger than wrought iron that had become more costly. Rolling was much more advanced and could produce plates and angles in size and thickness greater than those in the original [1]. Relatively small hot-rolled steel plates were spliced into unified bridge components by the clinching stresses from shrinkage of the rivets after being driven while red-hot. Moreover, in neither the 1858 Tube nor the 1898 Truss was the Canadian metallurgical industry sufficiently advanced to provide the ferrous structural materials; however, a Canadian bridge company participated in the reconstruction [1]. In 1958, to accommodate the St. Lawrence Seaway, a spur was built to switch traffic to one or the other operating lift spans. At the switch, two truss spans were replaced by girders under the tracks and the new spur in the bridge was built of rolled structurals with welded joints, so considerably lighter [1,31]. Crossing the Rideau Canal in Ottawa, many old bridges with the truss below the roadway have been doubled in width during the past 30 years. Examination while skating on the Rideau shows that while the structural truss members have the same pattern, the new ones are hot-rolled shapes (thus no rivets along their length), the joints are all bolted and occasional bracing for the side rails are welded.

The culmination of truss-style bridge was the cantilever, such as the record-setting Quebec Bridge, where the combinations of one side span (~165 m) and half the center span in each (~274 m) are supported by tall towers (93 m) over the piers [17,20,32,33]. The upper tension members are composed of simple pinned eye bars (as in the Menai suspension bridge). Because of the height and span length, the compression members must have large total sections to prevent buckling, being composed of braced I-beams of much smaller total section to keep the stress well below that for yielding [17,20,32,33]. There must also be various vertical and diagonal members to provide stability for not only dead and traffic loading but also for lateral wind loading. Because the truss sags under gravity (20 m at the tip of the Quebec center span), the lengths of members and of bays are different from those under no-load in the shop [17,20]. Even though bays are joined by pinned connections (no bending moments), it was often necessary in other bridges to use jacks to get rivet holes aligned [17,20,31,32]. In the Quebec Bridge K-bay design, each bay is completely riveted before the next bay is added, making construction easier and safer [17]. Organization of the bridge members, the shape of each sub-structure and the order of fabrication have to be designed in such a way that the necessary rivets can be driven. Fabricated components are shipped to the construction site with all the necessary holes and exact dimensions [13,17,20].

6. CONCLUSION

Hot driven rivets, which were a comparatively novel extension of a very old technology, were essential for the new wrought iron and steel age (1780-1930), since semi-rolled products were of comparatively small size. With suitable rivet spacing, the clinching effect from thermal shrinkage (raising rivets to their yield stress) produced a joint that was leak tight for boilers and ship hulls and that spliced bridge members at stresses above the permitted material design limit. Bolts that, until about 1850 were made by hand, did not compete until suitable torque wrenches and high tensile strengths were developed about 1950. Welding became practicable about 1930 but suffered many disasters for several decades before becoming a trustworthy alternative in ship and bridge construction. Of course, the great increase in dimensions of rolled plates and of I and H beams from universal mills greatly decreased the need for joining. Presently, the only major utilizations of rivets are in aircraft where rivets are employed extensively, but they are cold driven.

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Hot Driven Rivets Essential Bond For Iron Plates (cont)

TABLE 1: HOT DRIVEN RIVETS

HEATING CHERRY RED, 980°C,, PORTABLE FORGE (RIVET BOY)
AUSTENITE GOOD DUCTILITY, STRENGTH 25% OF THAT COLD
- HEATING TO 1260°C, LONGER TIMES NEGLIGIBLE DAMAGE
- (CONCERN FOR GRAIN GROWTH, DECARBURIZATION)

RIVET INSERTED, HELD BY 12 POUND HAMMER (HOLDER)
RIVET DRIVEN BY BLOWS FROM 9 POUND HAMMERS,
- (2 RIVETERS ALTERNATELY). [300 RIVETS PER SHIFT]

IN SHOPS, HYDRAULIC C SHAPED RIVETERS; IN FIELD,
PNEUMATIC GUNS WITH BUCKING BAR HOLDER.
RIVET SHANKS EXPAND TO FILL HOLES NEAR HEADS
WORKING AS FERRITE ENHANCES STRENGTH 10-20%
HEADS CLAMP LIGHTLY DUE TO DRIVING PRESSURE
CLAMPING FORCE RAISED BY 0.9% THERMALCONTRACTION

TABLE 2: PROCEDURE FOR RIVETED JOINTS

SYMMETRICALLY OVERLAPPING PARTS OR SPLICING PLATES
- 2-3 RIVET ROWS SPACED ~4 DIAMETERS IN EACH PIECE.

STRUCTURAL STEEL SHOP, SHIPYARD, (PLATER)
PLATES CUT, BENT TO DESIRED CONTOURS. TO ANGLES
- HOLES DRILLED OR PUNCHED. 1.5MM CLEARANCE
- ASSEMBLED, CLAMPED., MATCHING HOLES REAMED

CLAMPING FROM CONTRACTION GIVES WATERTIGHT JOINT .
- PREVENTS SLIP OF PLATE SPLICES BEHAVE LIKE ONE PIECE.
- POSSIBLE PROBLEMS WITH CREVICE CORROSION

RIVETS REPLACED BY HIGH STRENGTH BOLTS TIGHTENED
- BY TORQUE WRENCH TO DEFINED, CONSISTENT CLAMPING
- FORCE. ALLOWED DESIGN STRESS (50-80% YIELD)

EASIER TO INSTALL, LESS EQUIPMENT.,ONLY ONE WORKER
(Mercier Bridge repair: workers remove loose rivets, replace with bolts)

TABLE 3: RIVETS - COLD-HEADED RODS

HOT ROLLED RODS. DIAMETER 0.5- 4CM. (STEEL MILL)
HEAD DEVELOPED BY COLD UPSET FORGING WHILE CUT
- TO LENGTH SHANK HELD (FASTENER FACTORY)

WROUGHT IRON – LONGITUDINAL SLAG STRINGERS BULGED
-INTO THE HEAD RETARDING HEAD-SHANK CRACKS
CURRENTLY 2 GRADES SPECIFIED BY ASTM 502

	YIELD		TENSILE	ELONG.	SHEAR 1”
LOW C STEEL	40KSI	275MPA	415MPA	25%	15KPS 34KG
Mn STEEL	56KSI	85MPA	525MPA	20%	

PLATES, SHEETS ROLLED, SLIT OR SHEARED, *(STEEL MILL)*
COMPONENTS FLAME CUT, BENT, SHAPED *(Fabricators Shop)*

TABLE 4: RIVETER'S EXPERIENCE *(James McQueen 1900-1976)*

PRACTITIONER OF CRAFT ON SHIPS, SCOTLAND (CLYDE BANK)
1914-1919: APPRENTICE, JOURNEYMAN HAND RIVETER
- (CLYDE YARDS UNDERGO POST WAR CRASH)
1920-1927: APPRENTICE, JOURNEYMAN BREWER AND DISTILLER
1928-1932: RIVETER, CAR PLATER (BROOKLYN MOTOR TRANSPORT)
1933-1939: MASTER BREWER, DISTILLER
1939-1947: FORMED RIVETING TEAM TO REPAIR WAR DAMAGED
- SHIPS IN HIDDEN YARD (FORTH BRIDGE, Scotland, East Coast)
1948-1965: BOILERMAKER, SHIP REPAIRS, MONTREAL

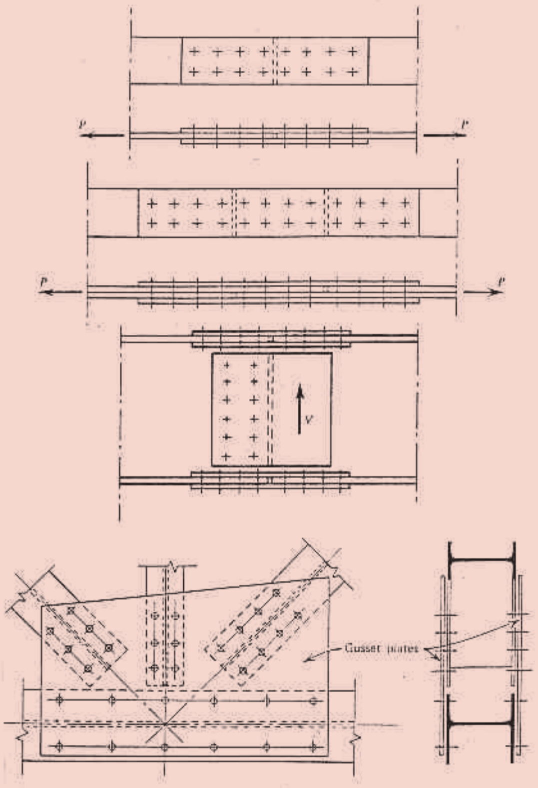


Figure 1 (a)

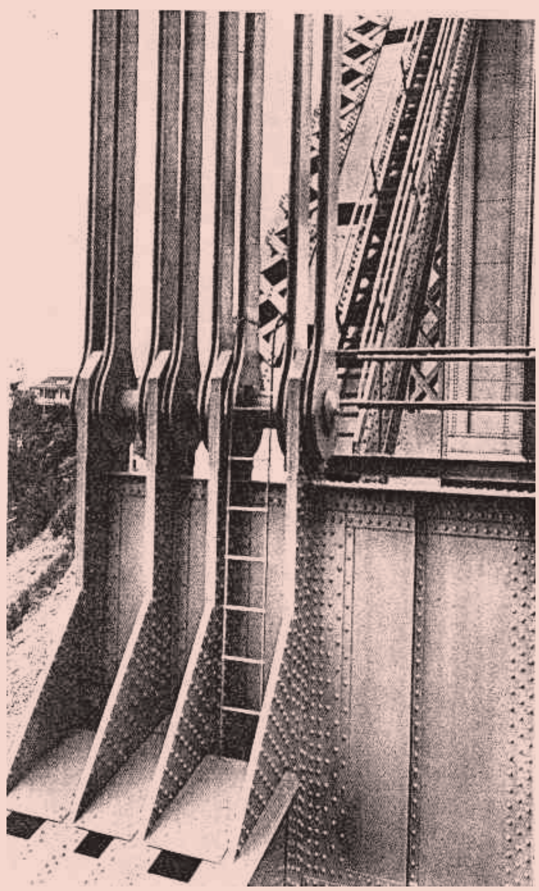
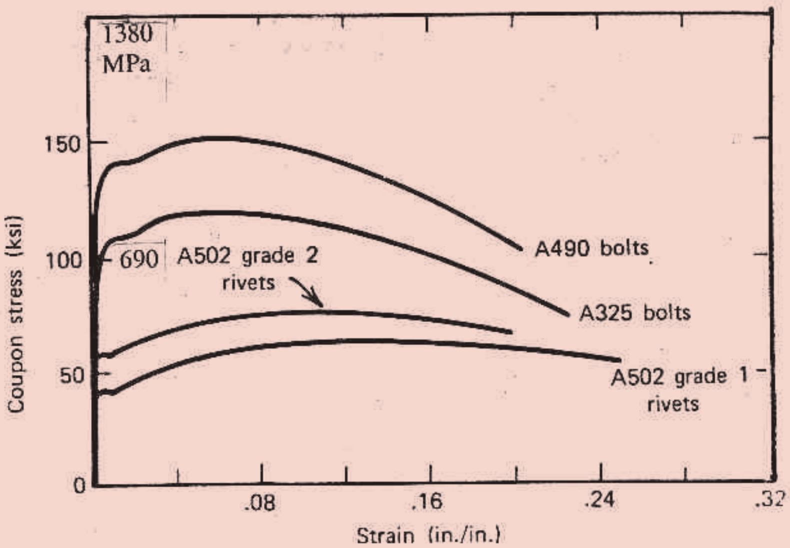


Figure 1 (b)

Figure 1. Examples of riveted joints: a) variety of types in trusses: longitudinal splices in plates, flange and web splices, connections of horizontal and vertical beams [13]; b) assembly of plates and angles of a transverse floor beam at the connections to the lower chord girders and to tension eye-bars with pins (from the Quebec Bridge). [1,14,17].



	Grade 1		Grade 2	
	Min.	Max.	Min.	Max.
Rockwell B	55	72	76	85
Brinell, 500-kg load, 10-mm ball	103	126	137	163

Figure 2. The properties of two grades of rivets are shown: a) in stress-strain curves in comparison with high-strength bolts (not available before1950) and b) in a table of hardnesses. (Grade 1: 0.19C-0.5Mn; Grade 2: 0.25C-1.5Mn.) [1,16].