

Metals used in old Bridges in Sri Lanka and the Effects of their Material Properties on Capacity Estimations

C.S. Bandara, J.A.S.C. Jayasinghe, P.A.K. Karunananda and U.I. Dissanayake

Abstract: Most of the metal bridges that were built over 100 years ago are still in use in Sri Lanka. To ensure the safety of these bridges as well as their users, condition assessment of these old structures becomes essential. The details of these bridges such as their mechanical and fatigue properties and the types of materials used in these bridges are very important for assessing their condition. Therefore, this study on metals used in old bridges was carried out using a literature survey and our own experiments. Recommendations were given thereafter for the selection of the mechanical and fatigue properties that are appropriate for assessing the old metal bridges in the country. The recommended values for the ultimate tensile strength of wrought iron and mild steel are in the ranges 284 – 390 N/mm² and 370 – 450 N/mm² respectively; values of yield strength of wrought iron and mild steel are in the ranges 191 – 241 N/mm² and 220 – 280 N/mm² respectively and, mean fatigue strength at 10 million cycles for both wrought iron and mild steel is 190 N/mm². Finally, the importance of selecting appropriate mechanical properties for estimating the current carrying capacity of metal bridges is presented using examples. It is observed that the error in the estimation of the carrying capacity of a bridge resulting from the use of inappropriate mechanical properties could be as high as 33%.

Keywords: Metal bridge, wrought iron, mild steel, material properties, condition assessment

1. Introduction

Metal bridges had been introduced to Sri Lanka in the 19th century with the development of its road and railway transport network [1, 2]. Even after 10 – 15 decades, most of these metal bridges are still in use. The fact that several old metal bridges such as “KaluPalama Bridge” on Galle – Deniyaya – Madampe Road and “Meeliyadda Bridge on Kurunegala – Keppitigala Road collapsed in the recent past, highlights the need for assessing the condition of old metal bridges in the country.

The bridge assessment process needs material properties of the bridge such as its composition microscopic details and its mechanical and fatigue properties [3, 4]. These details are useful for identifying the metal used in the bridge, estimating the strength and understanding the behaviour of the material during loading. They are useful in condition assessments for determining the load carrying capacity, remaining life and failure mechanisms of structural members such as ductile or brittle fracture and fatigue failure.

The determination of the material properties of a bridge needs testing of its metal specimens obtained from different structural members. The material properties of a bridge may differ from one member to another depending on the production quality of the old metals [5],

possible member replacements and material degradation due to fatigue and corrosion [6, 7].

Therefore to obtain material properties of an old bridge accurately, a large number of samples taken from different parts of the structure have to be tested which would certainly be a difficult task. Furthermore, if the samples do not represent the material properties of the entire bridge correctly, it may produce erroneous assessment results.

Some knowledge on the material properties of other metal bridges built during the same era will definitely assist in reducing the errors or the uncertainties relating to the material properties of any particular bridge.

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The first aim of this paper was to provide the important material properties of old ferrous metals used in bridge construction during the period from 19th century to early part of 20th century. In this study, material properties were obtained from the literature and also by testing the metals of several bridges.

It is important for engineers to understand the magnitude of the error that can result from the inappropriate selection of material properties in the assessments of old bridges. As the next aim of this paper, the load carrying capacities of two metal bridges were estimated by changing the metal type and its mechanical properties. Then, the percentage error in the capacity estimation was evaluated.

2. Methodology

Material properties of existing metal bridges were studied in two steps: (a) conducting laboratory tests using metals obtained from different bridges (built in the 19th and early 20th centuries) in the country. Tensile, hardness and fatigue tests were carried out to estimate strength properties while microscopical investigations were conducted to identify the metal, (b) studying the literature related to materials in old metal bridges. Local literature was used directly to obtain the material details of the bridges in the country while literature published in other countries was used to compare the properties of metals used in those countries in the 19th and early 20th centuries. The details obtained during these two steps were then analysed and a reasonable estimation of material and strength properties was made.

Material testing was carried out for randomly selected (or received from bridge authorities) samples. The standards used were ASTM E 8 M - 01: 2001 for the tensile test [8], ASTM E 18 M - 02 for the Rockwell hardness test [9] and BS 3518: 1962 for the fatigue test [10].

In order to estimate the magnitude (percentage) of the error caused by the inappropriate selection of material properties, Finite Element Models (FEMs) of two metal truss bridges were employed. The load carrying capacity of each bridge was estimated for four types of materials: (1) wrought iron - low strength (WI/L), (2) wrought iron - high strength (WI/H), (3) mild steel - low strength (MS/L) and (4) mild steel - high strength (MS/H). Then, the carrying capacities were compared and the percentage error was estimated.

3. Literature Survey on Metal Bridges in Europe and USA

Literature shows that the three main metals used in road and railway bridges during the period from the 18th century to early 20th century were cast iron, wrought iron and mild steel. Much needed information about these three metals is available in some of the recently published literature [5, 11, 12, 13, 14].

Cast iron has been used in bridge construction since the 18th century. The Iron-bridge at Colebrookdale, United Kingdom built during the period 1777 - 1779 is the world's first major cast iron bridge [15]. Cast iron contains over 2% carbon and thus is not weldable. Graphite flakes make cast iron brittle. Internal cracks can occur and propagate along these flakes due to tensile stresses and cast iron therefore is weak in carrying tensile and impact loads. However, cast iron has a good wear resistance making it a favoured metal for the bearing plates of many metal bridges. Tests conducted in 1969 on specimens taken from the Colebrookdale Iron-bridge showed that the Ultimate Tensile Strength (UTS) of cast iron is as low as 131 N/mm² and that its compressive strength is 208 N/mm²[15].

With the commencement of its production in the late 18th century, wrought iron (puddle steel) became a popular material for the superstructure of bridges due to its good tensile properties. The carbon content of wrought iron is less than 0.08%. The high amounts of phosphorus and nitrogen contained in wrought iron make it a brittle material. Wrought iron also contains slag layers (sulphates and oxides) deposited during its production. The weldability of wrought iron is also low necessitating the use of rivets to connect wrought iron members. One of the best-known wrought iron structures is the Eiffel Tower in France built during the period 1887 - 1889. According to Bowman and Piskorowski [11], the experimental work of Kiraldy, Humber and Beardslee conducted in 1860s showed that the average UTS, Yield Strength (YS) and Elongation (EL) of wrought iron were 372 N/mm², 228 N/mm² and 23.2 % respectively.

The production of mild steel in the 1850s made a huge change in the metal industry due to the strength, ductility, impact resistance and weldability of mild steel. Therefore, in the early 20th century, mild steel was the main material used for metal bridges. The early mild steel produced in the 19th century contained many

Table 1- Chemical composition and mechanical properties of old metals used in bridges

Description	Chemical Composition (%)					Mechanical Properties		
	C	Mn	Si	S	P	UTS	YS	EL
Cast iron	> 2.0	0.2 - 1.2	0.3 - 3.0	< 1.2	< 1.0	90 - 135		0
Wrought iron	0.08 - 1.0	< 0.4		< 0.04	< 0.6	280 - 400	220 - 310	5 - 20
Mild steel (before 1900)	0.02 - 0.15	0.2 - 0.5	0.08	0.02 - 0.15	0.03 - 0.07	370 - 440	> 220	≈ 20
Mild steel (1900 - 1940s)	0.1 - 0.2	0.4 - 0.5	0.08	0.01		370 - 450	240 - 280	15 - 25

Note: UTS: Ultimate Tensile Strength in N/mm², YS: Yield Strength in N/mm², EL: percentage elongation at fracture

impurities due to which the variation of its mechanical properties was high. However, mild steel produced in the 20th century was reasonably good in quality.

JRC Report [5] provides details on the chemical composition and mechanical properties of metals used in old metal bridges in Europe. These details are reproduced in Table 1.

The mechanical properties recommended in the JRC Report [5] for YS of old mild steel in Europe is 230 N/mm² and it was 200 N/mm² for wrought iron with the Young's modulus standing at 210GPa (at +10°C) for both metals. Larsson [9], considering the

experimental data (tested at 0°C to -30°C) of old bridges built in Sweden and Germany, has mentioned that the characteristic YS and UTS of mild steel in bridges built between 1919 and 1940 is 220 N/mm² and 350 N/mm² respectively and that the strength reduction for bridges built between 1901 - 1919 should be 20% and that for bridges built before 1900 it should be 45%. Berman et al.[11] have stated that the recommended shear strength for rivets in bridges built before 1936 in the USA is 124 N/mm².

Fatigue properties are the other material properties important in metal bridges. The Stress - Life (S-N curve) proposed in the JRC Report [5] for fatigue damage assessments of old riveted wrought iron and mild steel bridges is the Detail C71 curve of EN 1993-1-9: 2005 [16]. Figure 1 shows the comparison between Detail C71: S-N curve and the actual full scale fatigue test data obtained from the literature [12, 17].

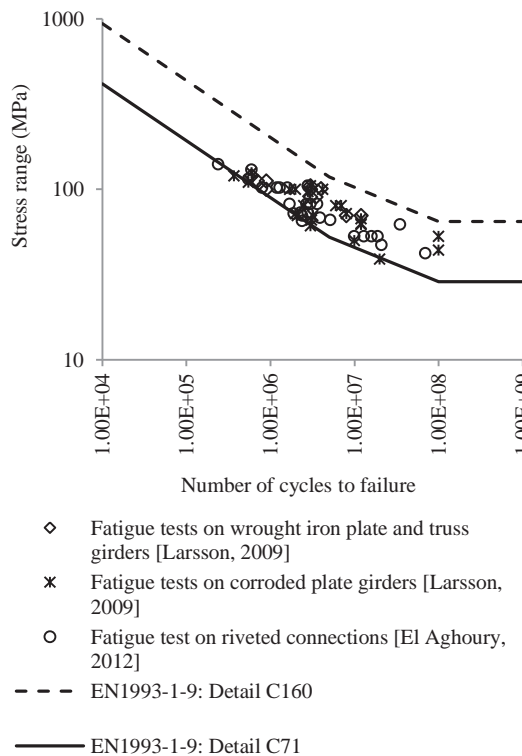


Figure 1 - Full scale fatigue tests data and Detail C71: S-N curve recommended for old metal bridges (Log - Log Plot)

4. Studies done on the Metal Bridges in Sri Lanka

The three major metals used in road and railway bridges in Sri Lanka before mid-20th century were cast iron, wrought iron and mild steel. The Transactions of the Engineering Association of Ceylon published during the period from 1908 to 1939 [18, 19, 20, 22] show that cast iron had been widely used for bridge piers and bearing plates. Buckle [19], mentions that the road bridge between Mannar Island and the mainland had piers built with cast iron outer cylinders, wrought iron inner cylinders with concrete filling the gap between the cylinders. The study made by Siriwardane et al. [3] shows that the piers of Kelani Railway Bridge built in 1885 are made of cast iron filled with concrete.



Table 2 - Mechanical and fatigue properties of iron and steel in bridges built before mid-20th century in Sri Lanka

Name of the bridge	Age (years)	Specimen location	Material	UTS	YS	EL	HRB	FS
KelaniRailway Bridge	> 130	Diagonal truss member	Wrought iron	328	241	17	57	165
BattuluoyaRoad Bridge	> 100	Diagonal truss member	Wrought iron	343	230	17	58	160
BattuluoyaRoad Bridge	> 100	Rivet	Wrought iron	390	--	--	67	--
RakwanaRoad Bridge	> 100	Truss member	Wrought iron	284	191	16	63	--
RakwanaRoad Bridge	> 100	Angle connector	Wrought iron	337	212	20	--	--
RakwanaRoad Bridge	> 100	Bolt	Wrought iron	341	239	21	--	--
KatugastotaRoad Bridge	> 150	Main lattice member	Wrought iron	338	229	18	--	--
KelaniRailway Bridge	> 130	Pier	Cast iron	165				
SenarathgamaRailway Bridge	> 100	Lattice connecting plate	Mild steel	434	302	29	65	205
MaggonaRailway Bridge	> 100	Plate girder	Mild steel	552	406	21	--	260
NarahenpitaRailway Bridge	> 100	Girder	Mild steel	426	250	37	67	200
MeeliyaddaRoad Bridge	> 100	Gusset plate	Mild steel	372	233	30	68	--

Note: UTS: Ultimate Tensile Strength in N/mm², YS: Yield Strength in N/mm², EL: percentage elongation at fracture, HRB: Rockwell hardness (B scale) and FS: constant amplitude rotary bending fatigue strength at 10⁷ cycles.

Wrought iron was the mostly used metal for the superstructure of bridges built before 1900. Bridges such as the KatugastotaRoad Bridge built in 1860 [21], WarakatotaRoad Bridge on Colombo - Ratnapura - HalpeRoad built in 1863 [20], PeradeniyaRailway Bridge built in 1867 [6], KelaniRailway Bridge built in 1885 [3], GalbodaRailway Bridge built in 1885 [6] and KanganinadeiRoad Bridge in Kalmunai built in 1904 [18] had been originally built with wrought iron.

Mahadeva[21] states that the KatugastotaRoad Bridge was strengthened in 1905 by adding new truss girders below the existing trusses that were made of mild steel. According to Hyde [20], the main span of WarakatotaRoad Bridge was replaced in 1913 with new bowstring trusses made of mild steel. Wijeyesekera [6] mentions that PeradeniyaRailway Bridge was strengthened using steel members after it was damaged by floods in 1947 and that one span of the GalbodaRailway Bridge was replaced with mild steel plate girders in 1950. These show the transformation of superstructure materials of bridges in Sri Lanka from wrought iron to mild steel. This further verifies the possibility that both wrought iron and mild steel can be found in a single bridge.

Some recent studies done on old metal bridges in Sri Lanka such as the fatigue damage assessment of KelaniRailway Bridge [3], reliability based life prediction of wrought iron bridges [22], condition assessment of metal railway bridges [23, 24, 25, 26], finite element analysis of truss type steel bridges [27] and retrofitting of damaged bridges [4] can be found in the literature. However, most of these studies mainly discuss the assessment processes and do not focus much on material details.

5. Details of Metals used in old Bridges in Sri Lanka

The mechanical and fatigue properties (mean values) of the metals used in the bridges built in Sri Lanka before mid-20th century are given in Table 2. Microscopical investigations show that the materials of all tested bridges are cast iron, wrought iron or mild steel. Figure 2 shows the wrought iron and mild steel microstructure of some of the bridges in the country. Figure 3 shows the fracture surface of wrought iron and mild steel formed when subjected to the rotary bending fatigue test. The brittle fracture surface of wrought iron and smooth crack propagation of mild steel are visible in this figure. All the tests except the one on KatugastotaRoad Bridge, were carried out at the Faculty of Engineering, University of Peradeniya (test data

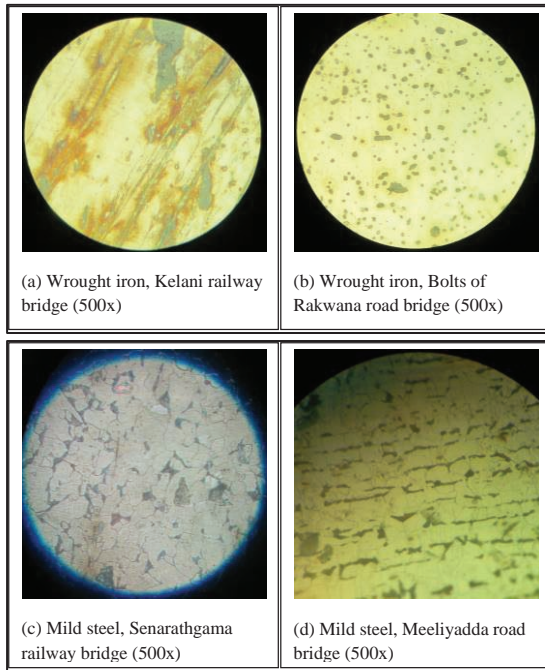


Figure 2 - Microstructure of old metals: (a) and (b) show wrought iron microstructure: Ferritic, inhomogeneous grain distribution with oxides and slag, (c) and (d) show mild steel microstructure: Ferritic - Pearlitic, homogeneous grain distribution.

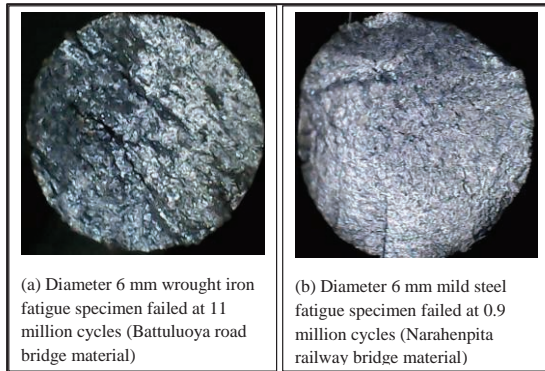


Figure 3 - Fracture surface of fatigue specimens, (a) brittle like fracture in wrought iron, (b) clear and smooth crack propagation and fracture in mild steel

of Katugastota Road Bridge was obtained from Mahadeva[21]).

5.1 Mechanical Properties

A statistical evaluation was carried out using the experimental data of 45 tensile specimens (the mean values of some of them are given in Table 2) to determine the values for UTS and YS of both mild steel and wrought iron used in the country. It was observed that the mean value of UTS is 372 N/mm² and that the mean value of YS is 256 N/mm². Statistical evaluation showed that the Standard Deviation (SD) for UTS is 62 N/mm² and that it is 44 N/mm² for YS. Figures 4 and 5 show the tensile test results, mean

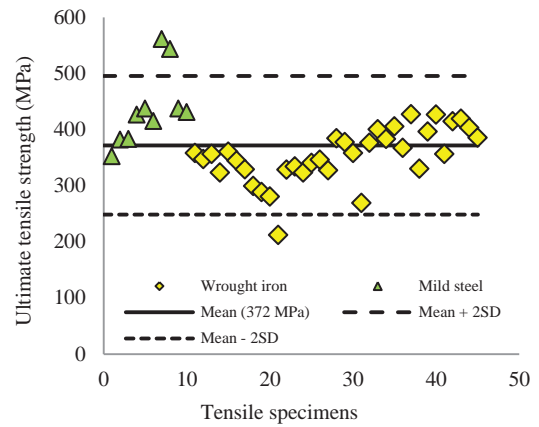


Figure 4 - Variation of ultimate tensile strength of wrought iron and mild steel

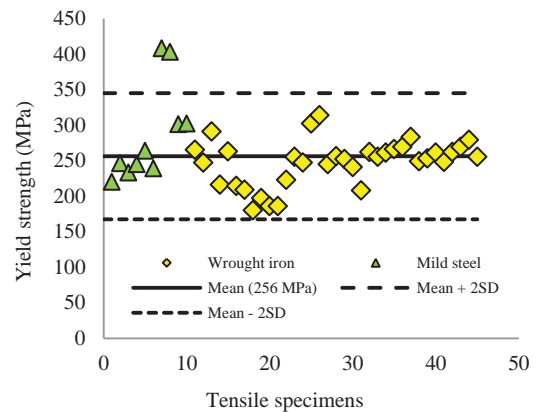


Figure 5 - Variation of yield strength of wrought iron and mild steel

values and $2 \times SD$ limits (for 95% confidence). Statistical evaluation shows that “Mean - $2 \times SD$ ” values are sufficiently safe for the assessment of old metal bridges in the country. However, for critical bridges and detailed assessments, at least a few samples may be tested for further verification.

Experimental values for Young’s modulus of wrought iron and mild steel can be found in the literature. The tensile test carried out on the wrought iron obtained from Kelani and other bridges shows that the Young’s modulus of wrought iron is 195 GPa[3, 25]. The Young’s modulus of the mild steel of Senarathgama and Maggona Railway Bridges is 200 GPa[23, 24].

5.2 Fatigue Strength

The fatigue strength of wrought iron and mild steel was investigated for High Cycle Fatigue (HCF) using more than 40 specimens. The required material was obtained from three wrought iron bridges and 3 mild steel bridges. Fatigue test was carried out at the Faculty of Engineering, University of Peradeniya using a constant amplitude rotary bending fatigue



tester. Figure 6 shows the S-N curve developed from the test results, the mean S-N line and $\pm 20\%$ lines. The mean fatigue strength at 10 Million cycles is 190 N/mm². The - 20% S - N line seems safe for fatigue life assessments. However, the variable amplitude nature of actual loading cycles, stress concentration and corrosion effects will have to be considered when determining the actual fatigue strength.

6. Effects of Material Properties on Capacity Estimations of Bridges

Structural assessments are very important for bridges that have been in use beyond their design lives or for bridges that have been subjected to increased service loading far above the design service loading and to deteriorations such as corrosion and accidental loading. In structural assessments, the identification of the metal type and the determination of the appropriate material properties such as mechanical and fatigue properties are very important. In order to investigate the effect of mechanical properties on loading capacity assessments, two common types of metal truss bridges were used in this study. The truss type in Bridge 1 is Pratt truss and that in Bridge 2 is Double Warren truss. The Finite Element Models (FEM) of these two truss bridges are shown in Figure 7. The four steps involved in this capacity estimation are discussed below.

Step 1: The materials of both bridges (FEMs) were considered as wrought iron. The Young's modulus (195 GPa) of wrought iron was assigned for the FEMs. Poisson's ratio used was 0.3. Then, the low strength values of wrought

iron (denoted as WI/L in Table 3) were assigned to FEMs. Both bridges were loaded with a Uniformly Distributed Load (UDL). The UDL was increased until the first member of each bridge failed. The UDL values at the time of this failure were recorded as the carrying capacities of the bridges (Table 4).

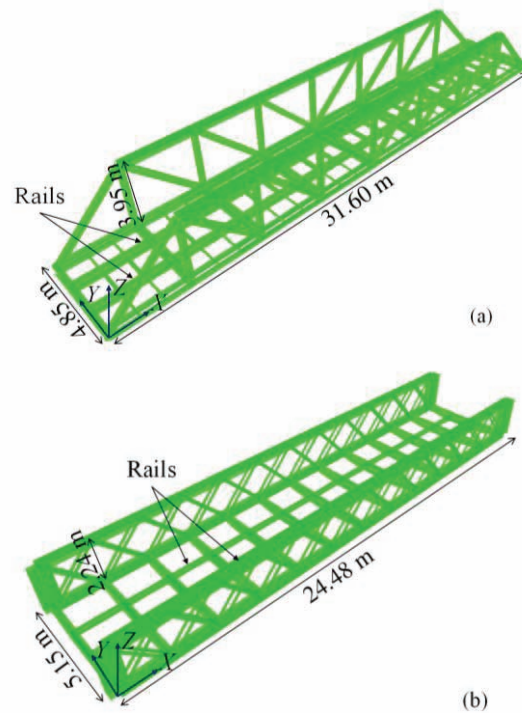


Figure 7 - Target steel bridge structures: (a) bridge-1: Pratt Truss and (b) bridge-2: Double Warren Truss

Table 3 - Material details and strength values assigned to FEMs

Material	Mild steel	Wrought iron
Young's Modulus E (GPa)	200	195
Poisson's Ratio ν	0.3	0.3
Low Strength	MS/L	WI/L
Minimum UTS (N/mm ²)	335	256
Minimum YS (N/mm ²)	210	172
Average UTS (N/mm ²)	372	284
Average YS (N/mm ²)	233	191
High Strength	MS/H	WI/H
Minimum UTS (N/mm ²)	497	309
Minimum YS (N/mm ²)	365	217
Average UTS (N/mm ²)	552	343
Average YS (N/mm ²)	406	241

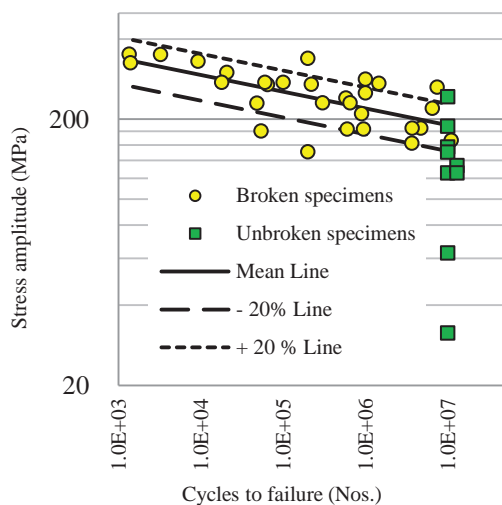


Figure 6 - Fatigue strength variation of wrought iron and mild steel (on Log - Log Plot)

Step 2: Without changing the material, high strength values of wrought iron (denoted as WI/H in Table 3) were assigned to FEMs. A loading procedure similar to that of Step 1 was followed and the carrying capacities of both bridges were recorded (given in Table 4).

Step 3: The materials of both bridges were changed to mild steel by changing the Young's modulus (200 GPa) of the FEMs. Then, low strength values of mild steel (denoted as MS/L in Table 3) were assigned to the FEMs. The same loading procedure similar to that of Step 1 was followed and the carrying capacities of both bridges were recorded (given in Table 4).

Step 4: Without changing the material, high strength values of mild steel (denoted as MS/H in Table 3) were assigned to the FEMs. The loading procedure was similar to that of previous steps. Then, the carrying capacities of both bridges were recorded (given in Table 4).

Figure 8 shows the vertical (z direction) displacement of the bridges. In Bridge 1, the overstressed bridge members (Pratt Truss) were the middle top chord members and in Bridge 2 (Double Warren Truss) the diagonal truss members close to the supports were the overstressed bridge members.

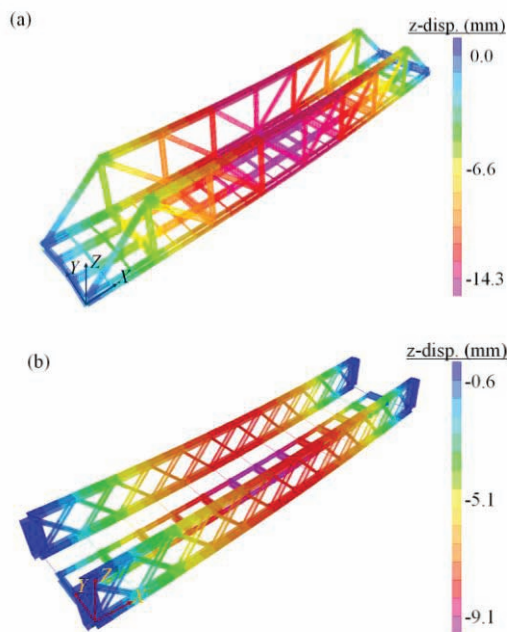


Figure 8 - Displacement in the z-direction (z-disp.) of bridge structures for MS/H material selection due to applied distributed load along rails: (a) Bridge-1 and (b) Bridge-2

Table 4 - Capacities of bridges and the maximum percentage error subjected to materials and the strength values assigned to FEMs

Bridge Number and Type	Material Type	Load Capacity (kN/m)	Error (%)
Bridge 1 (Pratt truss)	WI/L	13.50	0.00
	WI/H	14.75	9.26
	MS/L	16.00	18.52
	MS/H	18.00	33.33
Bridge 2 (Double Warren truss)	WI/L	8.25	0.00
	WI/H	9.25	12.12
	MS/L	10.00	21.21
	MS/H	11.25	36.36

As shown in Table 4, if the material of Bridge 1 is wrought iron with low strength and if mild steel with high strength is used by error in the FEM, the error in the carrying capacity could be 33.3%. If this same material selection error happens in Bridge 2, the error of the carrying capacity could be 36.4%. Therefore, this investigation highlights the importance of using correct material properties in the assessments.

7. Discussion and Conclusions

The recent collapses of old metal bridges in Sri Lanka show the need for assessing the old bridges. The material properties of these old structures are among the most important data required for the assessments. The present study provides these much needed material properties of metals used in the country from the 19th to early 20th centuries.

The comparison of the mechanical properties shows that the UTS values of wrought iron used in the bridges in the country (i.e. 284 - 390 N/mm²) fall within the range found in the literature (i.e. 280 - 400 N/mm²). However, the value of YS of wrought iron used in the local bridges does not agree with the values given in the literature. Therefore, a value within the range 191 - 241 N/mm² found by testing the wrought iron of local bridges can be recommended for the YS. The UTS of mild steel of local bridge materials is in the range 372 - 552 N/mm² and the lower value is within the range provided in the literature (i.e. 370 - 450 N/mm²). The lower value of the range of YS of mild steel of local bridges (233 - 406 N/mm²) slightly deviates from the range given in the literature (i.e. 220 - 280 N/mm²). Statistical



evaluation shows that the mean UTS of both wrought iron and mild steel is 372 N/mm² with a SD of 62 N/mm². It also shows that the mean YS of each of the two metals is 256 N/mm² with a SD of 44 N/mm². The study shows that “Mean - 2 × SD” provides safe strength estimations.

The results of the constant amplitude rotary bending fatigue tests conducted using metals obtained from the bridges in Sri Lanka show that the fatigue strength of wrought iron at 10 million cycles is about 160 N/mm² with the fatigue strength of mild steel varying between 200 and 260 N/mm². The mean fatigue strength of old metals (i.e. wrought iron and mild steel) at 10 million cycles is 190 N/mm². However, a 20% reduction is needed to estimate a reasonably safe value for the fatigue strength (and S-N curves). Furthermore, the effects of variable amplitude loading, stress concentration and corrosion etc., also have to be taken in to account. As suggested in the literature, it can be mentioned that the Detail C71: S-N curve of EN 1993-1-9: 2005 [16] can also be used for fatigue damage assessments of metal bridges in the country.

The present study shows the significance of selecting appropriate material properties for bridge assessments. The investigation carried out using two truss bridges showed that the error in the estimation of the carrying capacity caused by the material details of a bridge could be as high as 33%. Therefore, the material properties recommended in this study or obtained from material tests should be used for assessing old metal bridges.

There are many other material properties such as fracture toughness, cyclic softening and hardening parameters, gigacycle fatigue properties, deterioration behaviour of old metals due to corrosion and corrosion fatigue that will be useful for the assessment of old metal bridges. These material properties are not available at present for the old structures in the country and therefore it will be essential to conduct further studies on this subject in the future.

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