

Bending Fatigue Tests and Finite Element Models of Steel Rectangular Hollow Sections [SRHS]

I. Ezz El-Arab*^a, W. Gray^b

^aAssistant professor, Structural Engineering Department, Faculty of Engineering, Tanta University, Egypt

^bBuro Happold Consulting Engineers, UK

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Abstract

The Welding in cold formed areas is not only an open question for statically loaded sections (brittle fracture) but also for dynamically loaded structures (fatigue resistance). A lot of structures are subjected to dynamic loadings and unfortunately very little information about the influence of welding in the cold formed areas on fatigue resistance is available. In order to establish the fatigue behavior of welded and non-welded rectangular hollow sections specimens, a large number of 4-point bending tests are performed at the Saud Bin Laden Group SBG with cooperation with Buro Happold UK, Laboratory for Steel. Because these tests are very expensive, and because of the large number of parameters regarding the RHS to be investigated (steel grade, wall thickness, load distribution, boundary conditions), a number of finite element models for these specimens are made. By modeling the specimens with different types of finite elements (shells, solids) and taking into account some types of loading distributions and boundary conditions, the obtained results (stresses, strains, displacements) from a static analysis are compared with those obtained from the real 4-points bending tests. In this way, the obtained conclusions would lead to decrease of the number of the specimens that need to be tested as well as the costs of the project. Furthermore, by using finite element analysis, many factors with direct influence on the fatigue resistance can be considered.

Key Words: Bending Fatigue; Steel rectangular hollow section; SRHS; Finite element model

1. Introduction

In the second half of the sixties, several studies and verifications of the steel hollow sections, their most important characteristics and also the joining techniques were conducted.

The hollow sections have become a very important structural element, both for engineers and architects. About 150 years ago, the first rectangular hollow sections were used for the design of England Railway Bridge and the first elliptical hollow sections for some other railway bridges. This was the beginning in the history of the steel constructions made of hollow sections. The first hollow sections were made of riveted or bolted plates and angles. During 20's continues rolling techniques have developed and welding techniques have introduced to the structural engineers. This was the start of industrial production of hollow steel profiles. Today many tubular sections are manufactured by welding plates and/or shells to each other.

Fatigue is important failure mode in many structural elements. During the past decades, several studies have been conducted in order to evaluate fatigue behavior of structural elements [1-3].

Concealations, welds in welded tubular section are Because of stress very sensitive to dynamical load. Therefore, systematically gained knowledge about the fatigue behavior of such structures is of great importance. The first tests on this problem were carried out in the 1980's. During these tests, circular hollow sections (CHS) braces flattened at their ends were welded to the corners of cold-formed rectangular hollow sections (RHS) chords, forming a K-joint. The results of these studies revealed that in the case of high material quality, welding in cold-formed areas does not necessarily have unwanted influence on the fatigue resistance.

Rutendo and Xiao-Ling [4] presented Welded thin-walled ($t < 4$ mm) tube-to-plate T-joints made up of cold-formed circular hollow sections welded onto a plate to

*Corresponding Author Email: islamezzelarb@yahoo.com

form a moment resistant connection used in the road transport and agricultural industry to manufacture equipment and other structural systems. Fatigue design of these joints is not available in the current standards. An understanding of the stress concentrations and failure in these connections is therefore necessary as a step towards understanding the fatigue behavior of these connections. Surface crack growth monitoring is used to obtain an approximation of the length of surface crack at the point of occurrence of a through-thickness crack. The relationship between surface crack length and the occurrence of a through-thickness crack is important in that it can be used as a measure of the criticality of a surface crack during structural health monitoring of equipment or structures.

MASHIRI and ZHAO [5] presented Galvanized sections that are suitable for use in the road transportation agriculture and rehabilitated structures. The structural systems in which galvanized sections can be used include chassis boxes, roof frames, base frames and drawbars among others. Since these structural systems are subjected to cyclic loading in service, are prone to fatigue failure. In Australia, galvanized sections, commonly known as Dura Gal, are thin-walled with wall thicknesses less than 4 mm. There are currently no fatigue design rules for sections of thicknesses less than 4 mm. The connections under investigation, namely, cross-beam connections are not covered in current fatigue design guidelines. This paper reports on fatigue tests of cross-beam connections made up of galvanized rectangular hollow sections (RHS) and angle sections. Stress concentration factors were determined in typical connections to determine hot spot locations and to verify observed crack growth patterns in these connections. The fatigue test data obtained from high cycle fatigue tests are compared to existing fatigue design curves. Design curves for cross-beam connections are recommended based on deterministic methods and probabilistic analysis.

It is worth mentioning that all kinds of tests are very expensive and in order to have reasonable conclusions, several specimens must be tested. For this reason, with the development of the computational systems and finite element programs, the design of the structures consisting of different types of sections has become easier. The best solution is always obtained by the completion of the finite element analysis with the tests carried out in the laboratory.

The purpose of this paper is to present a comparison between some fatigue tests and the finite element analyses, using of different types of finite elements, loading and bearing conditions.

2. Description of Performed Tests and Finite Element Model

The fatigue tests are carried out as 4-point-bending-tests Figure 1, both on welded and non-welded specimens for comparison. For all static tests, the same material quality, wall thickness and chemical composition were used.

The test specimens chosen were rectangular hollow sections (RHS). Depending on the availability on the market, the specimens were different in sizes, wall thicknesses and corner radii. The general dimensions of test specimens are shown, as an example, in Table 1.

Table 1. Dimensions of test specimens

Dimension of test specimens	b x h x t (mm)
Specimen 1	100 × 100 × 5
Specimen 2	100 × 100 × 8
Specimen 3	100 × 100 × 10
Specimen 4	100 × 100 × 12.5

All the tests were performed with the test machines from the Laboratory for Steel at Buro Happold Laboratory. At first, all the specimens were measured and cleaned. A strain gage was applied to each specimen, on the tension side, on the edge in order to measure the values of the longitudinal stresses and strains. The position of this strain gage was on the mid length of the hollow section as shown in the Figure 1.

In the first stage, the load was applied on the specimen in steps of 2kN until the maximal value of the load of 10kN was reached. The position of the load and also of the saddles which sustain the specimens can be seen in Figure 1, of course with different values for c, x and d for each specimen. After reaching value 10kN of the load, the process was repeated in reverse direction, also in steps of 2kN. The reason of this operation was the calibration of the machine and for the measuring software and also the remove of residual stresses in the specimen.

Following that the load was applied again from 0 up to the maximum value of 10kN and back to 0, but this time the longitudinal strains were measured. The values for the longitudinal strains were:

- For a 150×150×5 hollow section:
 $\varepsilon_z = 0.098 \times 10^{-3}$ [$\mu\text{m}/\text{m}$],
- For a 100×100×5 hollow section:
 $\varepsilon_z = 0.279 \times 10^{-3}$ [$\mu\text{m}/\text{m}$]
In the same way, the stresses were established.
- For the 150×150×5 hollow section:
 $\sigma_z = 20 \text{ N}/\text{mm}^2$.
The theoretical value for the longitudinal stresses, determined by a hand calculation, depending on the chosen simplified static scheme, was of 27 N/mm^2 .
- For the 100×100×5 hollow section, the theoretical value for the longitudinal stresses, determined by a hand calculation was, of 65 N/mm^2 .

These values have a very large variation spectrum according to the specimen dimensions, loading and bearing conditions. Because the distribution of stresses and strains on the cross section of the hollow section and also the deformed shape of the specimen is hard to foresee, it was concluded that a finite element program can help to solve these problems.

The finite element program ANSYS was chosen. With this computer program, several types of finite elements can be chosen and several bearing and loading conditions can be simulated. ANSYS consists in calculation modules and integrated pre- and postprocessors for the data input and results presentation respectively [6, 7].

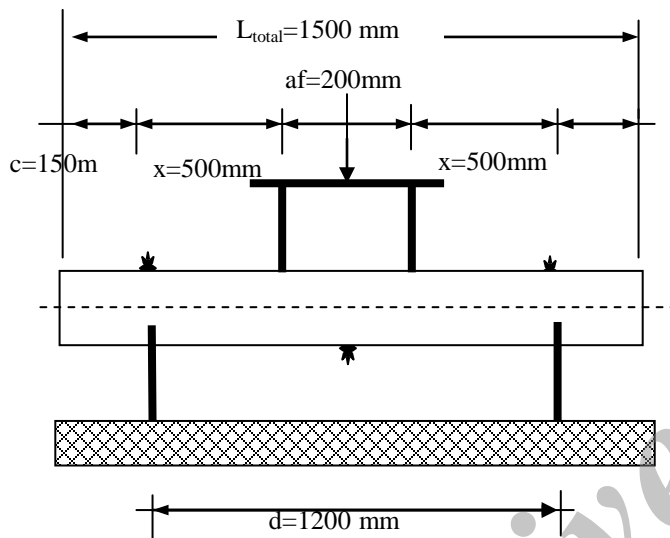


Figure 1. Scheme of the performed 4 point bending tests

* The position of the stress and strain gage on the tested

Three kinds of elements were chosen and presented from as Ansys element library follows:
The **SHELL63** element has both bending and membrane capabilities. It can support normal loads and the increase of loading in several steps. This element has 6 degrees of freedom, displacement and rotations at each node.

The **SOLID45** element is used for 3D discrete models of rigid structures. The element geometry is defined through eight nodes, with three degrees of freedom, displacements at each node. This element can support different types of analyses: plastic analysis, creep analysis, geometrical nonlinear analysis. It can also be used for large displacements, large bending problems.

The **SOLID95** is a higher order type of element **SOLID45**. It can be used to model irregular domains without significant lost of accuracy and is recommended for curved shapes. The element has 20 nodes with three degrees of freedom at each node. This element can support different types of analyses: plastic analysis, creep analysis, geometrical nonlinear analysis and can be used for large displacements, large bending problems.

The geometry, nodes position, and local axes system for these elements can be seen in Figure 2.

For all specimens, the finite models are created according to the conditions for the shape of the element, to the bearing conditions and distribution of loads. In the region of the specimen where the bearings and loads are placed, the finite element mesh was chosen very fine. For all the models using solid finite elements, at the beginning only one element on the thickness of the specimen was considered. After several analyses, the appropriate number of finite elements on the thickness of the specimen was established and this was kept unchanged for the rest of analyses. With help of the finite element analyses, the longitudinal and equivalent stresses and strains distribution was established. For all models, the behavior of the material was considered linear elastic.

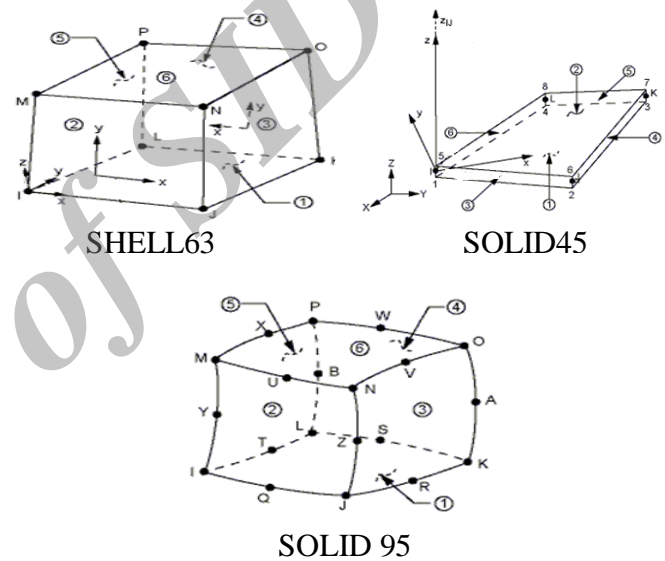


Figure 2. Finite element types used in the analysis [6]

The values of the longitudinal stresses (σ_z), longitudinal strains (ϵ_z) and displacement (d_y) in the middle of the specimen at the bottom part are presented in table 2.

Table 2. The values for σ_z , ϵ_z and d_y using different types of finite elements.

Type of finite element		ϵ_z (mm)	σ_z (N/mm ²)	d_y (mm)
SHELL63		0.248×10^{-3}	44.217	0.65
SOLID45	Inside	0.2577×10^{-3}	62.897	0.73083
	outside	0.2786×10^{-3}	51.485	
SOLID95	Inside	0.2577×10^{-3}	64.362	0.73050
	outside	0.2787×10^{-3}	52.073	
Hand calculation		0.311×10^{-3}	65.230	-
Test results		0.279×10^{-3}	-	0.76

3. Influence of the Load Distribution on the Values of the Stresses and Strains

Because of the test machine, the load is applied through a saddle (as shown in Figure 1) and the bearings are also represented by two saddles, in the finite element models. This was modeled by taking different distribution of loads and bearing surface outside of the specimen cross section. The values for the stresses and strains are obtained in the interpolation points of the finite elements.

For the models, only the SOLID45 elements are used. The length of the uniform distributed applied load is described through the variable d_f and the length of the bearing surface through the variable d_r . The scheme of the considered model is presented in Figure 3.

The values for d_f and d_r measured in the laboratory were: $d_f = 39$ mm; $d_r = 35$ mm. By taking into account different other values for d_f and d_r , the values for the stresses (σ_z), strains (ϵ_z) and displacements (d_y) are given in Table 3. The values for stresses and strains are measured inside and also outside the finite element placed in the middle of the model, in tension.

4. Conclusion

In this paper, some 4-point-bending test results and finite element models for rectangular hollow sections are presented. The type of finite element and also the modeling of external loads and bearing conditions have a strong influence on the obtained results.

Using finite elements, it can be seen that the results of the linear static analysis are close to those obtained in the laboratory. The best results were obtained using 8-node finite element SOLID45. The differences between the values numerical and test results were less than 10% (for example, for a hollow section 100x100x5 with corner radius of 12 mm, the differences were: for the longitudinal strains - 1.07%, for the longitudinal stresses 1.03%, for the displacement - 3.88%.

The finite element models cannot be a substitute for the tests in laboratory, but taking into account their results, their use can lead to a decrease the number of test sample.

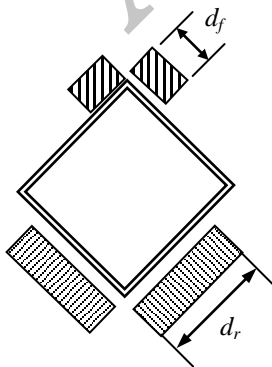


Figure 3. The distribution of the applied and bearing conditions

Table 3. Influence of the loads and bearing conditions on the values of σ_z , ϵ_z and d_y

Types of finite element		ϵ_z (mm)	ϵ_{eqv} (mm)	σ_z (N/mm ²)	d_y (mm)
SOLID45 $d_f=39$ mm $d_r=35$ mm	Inside	0.2577 $\times 10^{-3}$	0.32633 $\times 10^{-3}$	62.897	0.73083
	Outside	0.2786 $\times 10^{-3}$	0.41881 $\times 10^{-3}$	51.485	
SOLID45 $d_f=70$ mm $d_r=35$ mm	Inside	0.2645 $\times 10^{-3}$	0.313 $\times 10^{-3}$	62.035	0.71777
	Outside	0.2864 $\times 10^{-3}$	0.4092 $\times 10^{-3}$	55.263	
SOLID45 $d_f=39$ mm $d_r=70$ mm	Inside	0.2553 $\times 10^{-3}$	0.3236 $\times 10^{-3}$	62.720	0.70571
	Outside	0.2757 $\times 10^{-3}$	0.4178 $\times 10^{-3}$	50.616	
SOLID45 $d_f=70$ mm $d_r=70$ mm	Inside	0.2618 $\times 10^{-3}$	0.3280 $\times 10^{-3}$	61.749	0.69188

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