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Fatigue Life Prediction of Steel I Section Using Finite Element Simulation

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Abstract— Analytical study on artificially damaged steel I section is presented in the paper. The study is carried out using ANSYS 15.0 WORKBENCH fatigue tool. Experimental test results [1] are compared with analytical results obtained. Fatigue analysis of the same section is done using IS 800-2007 [General construction in steel-Code of practice]. For ANSYS 15.0 analysis Soderberg's theory of fatigue analysis is used. It is observed that ANSYS 15.0 gives fatigue life prediction in number of cycles on marginally safer side compared to experimental test results. Analysis using IS 800-2007 gives more fatigue life estimation than it was observed in actual experimental fatigue testing.

Keywords- Steel I Section; ANSYS 15.0; Fatigue life; Soderberg Theory; IS 800-2007

I. INTRODUCTION

Long ago, engineers discovered that if you repeatedly applied and then removed a nominal load to and from a metal part (known as a 'cyclic load'), the part would break after a certain number of load-unload cycles, even when the maximum cyclic stress level applied was much lower than its Ultimate Strength, and in fact, much lower than the Yield Stress. Steel bridges commonly contain structural elements that are prone to damage caused by repeated loading from vehicular traffic. Fatigue damage due to these cyclic loads tends to accumulate over time, with the primary adverse consequence being the formation of cracks in the steel structure. Fatigue is the phenomenon of decrease of resistance of the material to repeated loading and failure takes place at the magnitude of the stresses well below the ultimate yield strength of the material. Fatigue strength of homogeneous section is much more than a member having connections. Connections and damaged locations attribute to stress concentrations. It starts with crack initiation at points of stress concentration then crack growth and finally the member fails in fatigue due to no much area left to sustain further load. Different types of fatigue loading are distinguished by using load ratio (R) i) Repeated and Reversed Load (R= -1) ii) Partially Reversed Load (-1< R < 0) and iii) Repeated-One Direction Load (R=0). In this study partially reversed loading is applied load ratio, R=0.2.

II. EXPERIMENTAL TESTING ON STEEL I-SECTION [1]

2.1. Specimen Details

Standard hot-rolled H350 × 175 mm steel beams with a length of 3,000 mm were chosen in 'Experimental study on the fatigue behavior of steel beams strengthened with different fiber-reinforced composite plates' [1]. The height and width of a beam cross section were 350 and 175 mm, respectively, and the web and flange thickness were 7 and 11 mm, respectively. For simulating damage caused, two U-shaped notches with a width of 8 mm were cut on both sides of the tension flange at the mid span of beam, serving as the damage-sensitive regions. The length of the notches was maintained at 21.8 mm, with ±0.1 mm tolerance. A steel cover plate with a length of 3,000 mm and a cross section of 240 × 12 mm was welded on the outside surface of the top flange of the steel beams, to provide equivalency of dead load of concrete deck. 80 mm × 6 mm stiffeners were welded on both sides of the web at the loading and supporting points.

2.2. Fatigue Test

Specimen was tested as simply supported beam with a span of 2800 mm. Specimen was loaded in two point bending. Two point loads were applied using spreader beam on top flange at a distance of 250 mm from mid span of beam section. The fatigue test was conducted under constant amplitude cyclic load with a frequency of 4 Hz; 60% of the calculated yield load of the unstrengthened beam based on the mid span notched section was adopted as the maximum load applied for fatigue load P_{max} (200 kN) to simulate the combined effect of actual dead load and live load. 20% of the maximum load was adopted as the lower limit value P_{min} for fatigue load (40 kN) to simulate the effect of dead load with the load ratio R=0.2. Before the fatigue test, a monotonic load was applied at 10-kN increments until the maximum value of fatigue load P_{max} was reached.

In the specimen, crack had propagated to a visible size of approximately 5 mm when $10x10^4$ load cycles were reached. After $15.6x10^4$ cycles, the tension flange completely cracked, and the steel beam fractured instantaneously, unable to bear any further load cycles.

III. FATIGUE ANALYSIS ACCORDING TO IS-800:2007

Provisions given in this code are applicable for high cycle fatigue. Low cycle fatigue is that when component is subjected to $\leq 10^3$ cycles. High cycle fatigue is that when structure is subjected to 10^3 -10^9 cycles and cycles $\geq 10^9$ are considered as ultra-high cycles. Generally in low cycle fatigue i.e. case of earthquakes strain life fatigue analysis is done. In present case of high cycle fatigue stress life fatigue analysis was done. For the purpose of design against fatigue, different details (of members and connections) are classified under different fatigue class. The design stress range corresponding to various number of cycles, are given for each fatigue class in IS 800-2007 Code. Members subjected to cyclic loads and magnitude of stress range expected are designed referring to the fatigue classes. In present case analysis of the specified steel I beam section is carried out.

3.1. Analysis Steps

i) The values of stress range obtained from standard S-N curve shall be modified by a capacity reduction factor (μ)

$$\mu = (25/t_p)^{0.25} \leq 1.0 \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

Capacity reduction factor given in eq. (1) is applicable for plates of thickness greater than 2 mm.

ii) Partial safety factor for fatigue shall be based on consequences of fatigue failure:

a. Fail-safe structural component/detail is the one where local failure of one component due to fatigue crack does not result in the failure of the structure due to availability of alternate load path (redundant system).

b. Non-fail-safe structural component/detail is the one where local failure of one component leads rapidly to failure of the structure due to its non-redundant nature.

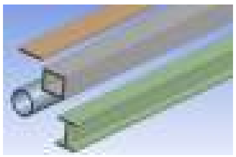
iii) Tables (2) indicates the classification of detail category for the purpose of assessing fatigue strength.

Table 1.Partial safety factor for fatigue strength (Υ_{mft})[2].

Sr No.	Consequence of Failure		
	Inspection and Access	Fail Safe	Non Fail safe

Sr No.	**Consequence of Failure**		
	Inspection and Access	Fail Safe	Non Fail safe
1	Periodic inspection, maintenance and accessibility to detail is good	1.00	1.25
2	Periodic inspection, maintenance and accessibility to detail is poor	1.15	1.35

Table 2.Detail category classification- Non welded details [2].

SI No.	Constructional Detail		
	Detail category	Illustration	Description
1	118		Rolled and extruded products ✚ Plates and Flats ✚ Rolled Sections ✚ Seamless Tubes Sharp edges, surface and rolling flaws to be removed by grinding in the direction of applied

iv) Fatigue assessment for variable stress range-

Fatigue assessment at any point in a structure, wherein variable stress ranges f_{fi} or τ_{fi} for n_i number of cycles (i =1 to r) are encountered, shall satisfy the following:

- For normal stress-

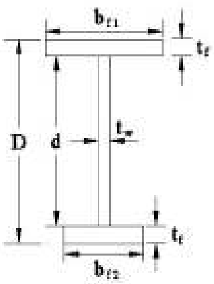
$$\frac{\sum_{i=1}^{\gamma_s} n_i f_i^3}{5x10^6\left(\frac{\mu f_{fn}}{\gamma_{mft}}\right)^3} + \frac{\sum_{j=\gamma_s}^{r} n_i f_i^5}{5x10^6\left(\frac{\mu f_{fn}}{\gamma_{mft}}\right)^5} \qquad \ldots\ldots\ldots\ldots.. (2)$$

- For shear stress-

$$\sum_{i=1}^{r} n_i \tau_i^5 \le 5x10^6\left(\frac{\mu f_{fn}}{\gamma_{mft}}\right)^5 \qquad \ldots\ldots\ldots\ldots. (3)$$

Where Υ_s is the summation upper limit of all the normal stress ranges (f_i) having magnitude lesser than ($\mu.f_{fn}/\ \Upsilon_{mft}$) for that detail and the lower limit of all the normal stress ranges (f_j) having magnitude greater than ($\mu.f_{fn}/\ \Upsilon_{mft}$) for the detail. In the above summation all normal stress ranges, f_i and f_j having magnitude less than 0.55 $\mu.f_{fn}$, and 0.55 $\mu.\tau_{fn}$ may be disregarded.

3.2. Sectional properties



For calculation of section properties notched section i.e. reduced section due to provision of notches is considered since it will provide least section modulus to resist the external applied forces.

Section details-

b_{fl} =175 mm b_{f2} = 131.4 mm t_w = 7 mm t_f = 14 mm d = 328 mm D=350mm I = 116.28x10^6 mm^4

For shear stress calculation I = 131.23x10^6 mm^4 since no notch provided at location of maximum shear stresses i.e. at supports and loading points.

$Z = 614.137 \times 10^3$ mm^3
Moment due to 200 kN load, M1 = 115 kNm
Moment due to 40 kN load, M2 = 46 kNm
Bending stress, σ_1 due to M_1 (f_{i1}) = 187.25 N/mm^2
Bending stress, σ_2 due to M_2 (f_{i2}) = 74.9 N/mm^2
Shear stress, τ_1 due to 2-100 kN loads = 45.9 N/mm^2
Shear stress, τ_1 due to 2- 40 kN loads = 18.306 N/mm^2.
For calculating shear stress near supports, area without stiffener was considered; since it will provide lesser cross sectional area to carry shear stress.

3.3. Fatigue Analysis

Capacity reduction factor is given by, $\mu = (25/t_p)^{0.25} \leq 1.0$
However maximum thickness is 11mm which is less than 25mm, therefore μ is taken equal to 1.0
Taking $\Upsilon_{mft} = 1.25$ for non-fail safe with periodic inspection, maintenance and accessibility to detail is good.
Using Variable stress range formulae for;

- Normal stress range- using eq. (1) we get $N = 16.2019 \times 10^4$ cycles
- Shear stress range- using eq. (2) we get $N = 18.14 \times 10^6$ cycles

Therefore actual fatigue life of I section is least of above two i.e. 16.2019×10^4 cycles

IV. ANALYSIS USING ANSYS 15.0

The 3D model of steel I beam section is generated in Ansys Design modeler. Same section which was used for experimental test [1] and analysis using IS code was modeled in Ansys. Small elementary areas having negligible thickness were created to apply point loads on top flange. To simulate the supporting condition used in experimental test [1] support sections were modeled. Two notches with a width of 8 mm were cut on both sides of the tension flange at the mid span of beam. The length of the notches was maintained at 21.8 mm. In actual test to simulate dead load of deck slab, plate of length of 3,000 mm and a cross section of 240 × 12 mm was welded on the outside surface of the top flange however in Ansys pressure producing same intensity of load i.e. 9.42×10^{-3} N/mm^2 was applied.

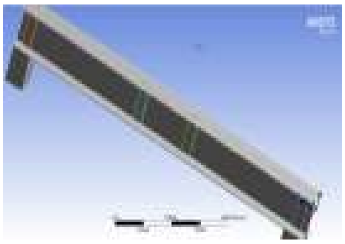


Fig 1.3D Model of section

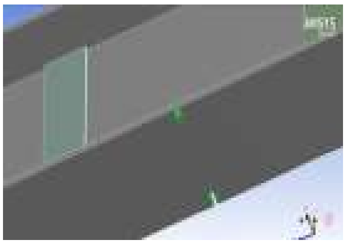


Fig 2.notches provided at mid span

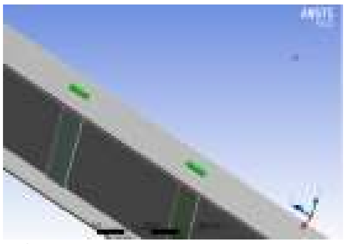


Fig 3.Elementary areas modeled

Two point loads of 100 kN each with loading ratio of 0.2 were applied 250 mm away from mid span on both sides. Maximum equivalent Von Misses stress developed was 185.15 N/mm^2.

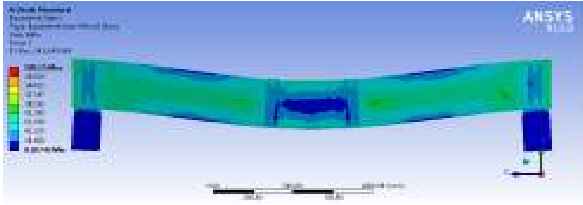


Figure 4. Point loads A& B applied

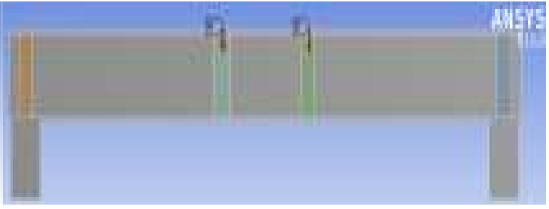


Figure 5.Equivalent Von Mises stress distribution

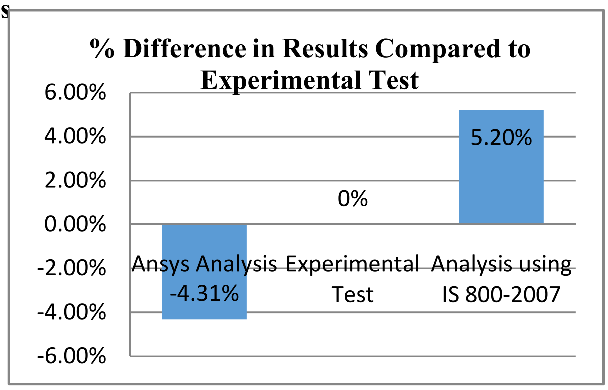
In Ansys for fatigue analysis Soderberg's fatigue theory is used. Soderberg theory gives conservative results compared to Goodman theory and Gerber theory. Equation of Soderbers's theory are given as:

$$\left(\frac{\sigma_a}{\sigma_e}\right) + \left(\frac{\sigma_m}{S_y}\right) = 1 \qquad \left(\frac{\tau_a}{\tau_e}\right) + \left(\frac{\tau_n}{S_{ys}}\right) = 1$$

Where, σ_a / τ_a - amplitude of normal/shear stress
σ_m - mean cycle stress
σ_e / τ_e – endurance limit at constant strength
τ_m - shear yield strength
S_y - yield tensile strength
$S_{ys} = S_y$ to $0.5S_y$ depending on material type ($0.577S_y$ for steel)
Result- Specimen fails at $14.736x10^4$ cycles

Table 1.Fatigue life results in number of cycles

SI No.	Method of evaluation	Fatigue life (number of cycles)
1.	Experimental fatigue test	$15.6x10^4$
2.	Analysis according to IS 800:2007 provisions	$16.2019x10^4$
3.	Analysis using finite element tool Ansys	$14.736x10^4$



V CONCLUSION

This paper presents study on the fatigue analysis based on the ANSYS finite element analysis, and comparing with the results of testing and with results based on IS 800-2007 provisions. In this paper high cycle fatigue analysis on steel I section which is commonly used in steel bridges. Fatigue life given by IS 800-2007 is higher (by 5.2%) compared to experimental test results. Fatigue analysis using Ansys 15.0 based on Soderberg's theory of fatigue analysis predicts life lesser (by 4.31%) compared to experimental test results. Considered section gave more fatigue life in shear stress compared to normal stress fatigue. Due to normal stress fatigue failure before final rupture of section significant yielding resulting in crack propagation is observed. This ensures ductile failure of section which will give advantage in repair and restoration of structure. The only variable factor used in analysis according to IS 800:2007 provisions is partial factor of safety for fatigue strength (Υ_{mft}). There should be inclusion of additional variable factors on which fatigue strength of structure would depend. Also in case of welded structures the weld fails due to stress concentration in welding process and applied cycles of load. In welded structures experimental fatigue testing should be done for section having similar sectional properties by varying its weld size.

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