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Analytical Study on Enhancement of Fatigue in High Strength Steel

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***Abstract*-By increasing the mechanical strength, the ratio between yield strength to tensile strength ratio will come closer to 1 and thus the elongation ratio will show significant decrease, representing a deterioration in the ductility and seismic response of high strength steel (HSS) and hence fatigue strength of HSS is reduced. Established analytical method to predict the fatigue life provides a sound and cost effective approach to study and enhance the fatigue behaviour of high strength steel. According to the literature study, the fatigue behaviour of FRP composites are very good, so in this paper fatigue behaviour of conventional HSS is Compared with Wrapped High strength steel (WHSS) using hybrid GFRP (glass fibre reinforced polymer) using varying percentage of Aluminium (Al) and titanium di oxide (TiO_2) analytically in ANSYS workbench. ASTM E606 test specimen is used for the fatigue study. GFRP laminates are fabricated with and without varying percentage of Al and TiO_2 as per ASTM D3039 for collection of data by tensile test. The fatigue test was conducted on 3 Nos of conventional HSS and 21Nos of GFRP wrapped HSS with varying percentage of Al and TiO_2 at stress ratio, R = min stress /max stress, -1.0 (tension-compression). And it is expected that fatigue life of WHSS will be increased.**

***Keywords:* Ductility, Seismic, HSS, Fatigue, hybrid FRP.**

I. INTRODUCTION

High strength steel (HSS) is well-defined as steel having a nominal yield strength not less than 430 MPa. Since recent developments of technology in material science and increasing call for high strength, HSS has been used in high-rise buildings, large span buildings and bridges in the past two decades. As far as seismic loads are concerned, Steel Moment Resisting Frames are reflected to be the most effective load resisting system. At the same time the call for energy dissipation due to cyclic loads in Steel structures using high strength steel is very high in the occasion of earthquakes. Therefore, enhancement of fatigue in the high strength steel is needed. A component or structure, which is designed to transmit a single monotonically increasing application of static load, may rupture and fail if the same load or even lesser load is, applied cyclically a large number of times. For instance, a thin rod bent backward and forward before yielding fails after a few cycles of such repeated bending. This is termed as the 'fatigue failure', is very high in the event of earthquakes. Cases of structures, prone to fatigue failure, are bridges, cranes, offshore structures and slender towers, etc., which are subjected to cyclic loading. The fatigue failure is due to progressive propagation of cracks in steel under cyclic loading. This is partially improved by the stress concentration at the tip of such flaw or crack. The stress concentrations may occur in the material due to some discontinuities in the material itself such as flaws, notches etc. The stress at these points could be three or more times the average applied stress. These stress concentrations are not important when a ductile material like steel is subjected to a static load, as the stresses redistribute themselves to other neighbouring elements within the structure. Stages in fatigue failures are Crack initiation, crack growth, crack propagation, and finally rupture.

A. Classification of fatigue failure

- High cycle fatigue ($N>10^5$ cycles)
- Low cycle fatigue ($N<10^5$ cycles)

B. S-N Curve and Fatigue Resistant Design

The most common form of representation of fatigue data is by using the S-N curve, where the total cyclic stress (S) is plotted against the number of cycles to failure (N) in logarithmic scale. A typical S-N curve is shown in Fig. 1. .It evidently shows that fatigue life decreases with respect to increase in stress range and at a limiting value of stress, the curve flattens off. The point at which the S-N curve flattens off is called the 'endurance limit'. To carry out fatigue life forecast, a linear fatigue damage model is used in conjunction with the relevant S-N curve. One such fatigue damage model is that postulated by Wohler as shown in Fig.1. The relation between stress and the number of cycles for failure could be written as

$$\log N = \log C - m \log S$$

where 'C' is the constant dependant on detailing category, and 'm' is the slope of the S-N curve.

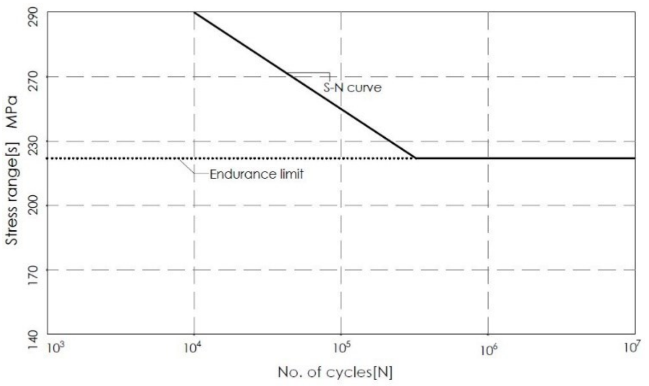

Fig 1 : S-N diagram for fatigue life assessment

C. Fatigue performance of FRP:

FRP has high strength to weight ratios, and excellent resistance to corrosion and environmental degradation. It is very flexible and forms all kinds of shapes, and is easy to handle during construction. The benefits of FRP strengthening method include the high strength-to-weight ratio, non-corrosive characteristics, ease of tailoring, and prompt execution on site. Of particular interest is the fatigue response of FRP composites, given that FRP-strengthened structures are frequently exposed to repeated loads (e.g., bridge decks and girders). Comprehensive summary of the FRP composites for strengthening concrete members subjected to fatigue; however, a detailed investigation on the fatigue behaviour of the FRP materials themselves, especially those emerging FRP composites, is still necessary. The fatigue response of FRP composites is dependent upon the constitutive fibres and varying filler materials (Al and TiO_2) and resin. Typical damage of FRP composites due to fatigue includes the matrix cracking, debonding, delamination, and fibre fracture. Fatigue-damaged FRP sheets may substantially influence the performance of strengthened structures.

There are many methods available to improve the fatigue of steel such as High frequency impact treatment method, Water jet peening, Laser peening, Rolling and grinding, Air blast cleaning treatment, Nano coating with ZnO coating, Wrapping by thin film metallic glass, Ni-Zn composite coating, FRP wrapping. Among these methods available, the method used in this project is FRP wrapping.

II. GEOMETRY AND MATERIAL PTOPERTY

A: Geometry and material used:

The high strength steel used for fatigue analysis is E630, the round steel bar is lathe worked to make fatigue dog bone specimen as per ASTM E606 as shown in figure 2. Glass fibre used is of E type and resin is polyester, and filler materials are Al, and TiO_2.

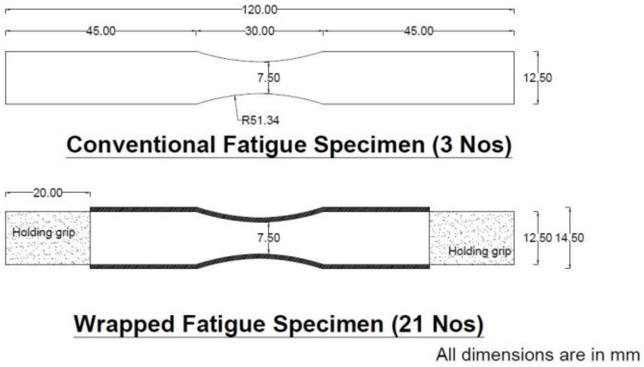

Fig 2 : ASTM E606 Specimen

B. Material Property:

Below are the material properties used for the ANSYS modelling

1. High strength steel:

Yield strength, MPa	630
Ultimate Tensile strength, MPa	800
Modulus of Elasticity, MPa	2.135×10^5
Poisson's ratio	0.295

2. GFRP composites:

The properties of GFRP laminates are obtained by fabrication as per ASTM D3039. Size of the laminate is 250 x 25 mm and fabricated as shown in fig.3

Fig 3 : GFRP composite polyester with and without Al and TiO_2

The above fabricated specimens are tested for tensile strength and tested in, and the results are shown in Table: 1.

TABLE I. MECHANICAL PROPERTIES OF GFRP LAMINATES

S. No	SPECIMEN ID	SPECIMEN DETAILS		THICKNESS mm	σ MPa	YOUNG'S MODULUS Mpa
1	GF	Conventional		1.72	79	18743.44
2	Al1	GF+Al	1%	1.6	41	23580.46
3	AL3	GF+Al	3%	1.8	68	19464.3
4	Al5	GF+Al	5%	2.1	87	19580.2
5	TiO1	GF+TiO	1%	1.8	27	19343.86
6	TiO3	GF+TiO	3%	1.6	105	21287.47
7	TiO5	GF+TiO	5%	2	73	20345.9

III. PROPOSED METHODOLOGY

A. *Material modelling:*

For the analytical work the model of dog bone specimen of E630 high strength steel and wrapped GFRP laminate is created in SOLIDWORKS and imported to WORKBENCH 15.0, then engineering properties are chosen for respective model and assigned. The model is meshed finely for the better result. Contact pair between high strength steel and GFRP is given as bonding.

There are totally 8 combination of specimens to be tested such as

1. Conventional HSS E650
2. Conventional GFRP wrapping
3. GFRP + 1% of Al wrapping
4. GFRP + 3% of Al wrapping
5. GFRP + 5% of Al wrapping
6. GFRP + 1% of TiO_2 wrapping
7. GFRP + 3% of TiO_2 wrapping
8. GFRP + 5% of TiO_2 wrapping

B. *Loading and support condition:*

Then bending fatigue load to be given to the specimen should be within the range of 0.5 to 0.9 times of ultimate fatigue strength. The formula used to calculate the fatigue load is,

$$P = \frac{\sigma \pi D^3}{32y}$$

Support condition used is fixed at one end which act as grip and bending load is given at other end.

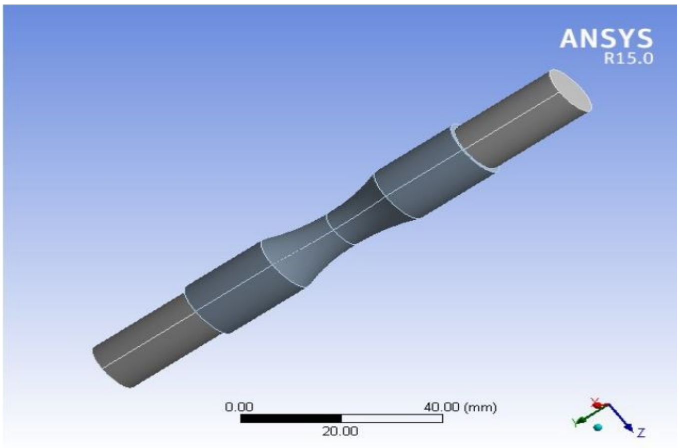

Fig 4 : Model of dog bone specimen of E630 steel

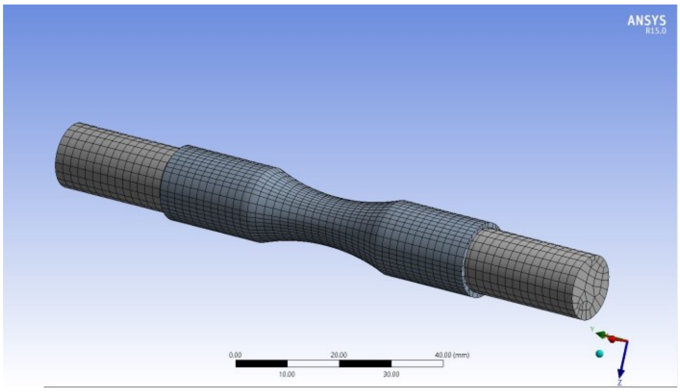

Fig 5 : Fine Meshing of specimen

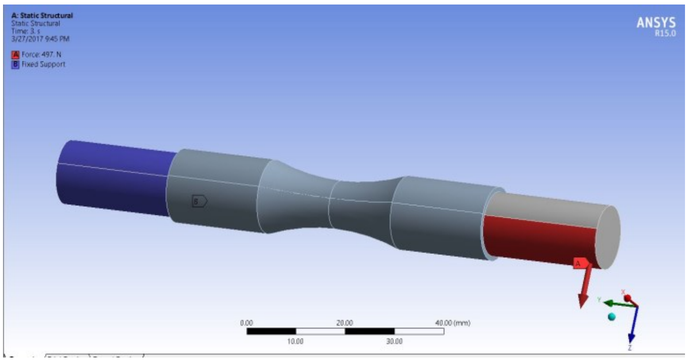

Fig 6 : Boundary conditions and loading

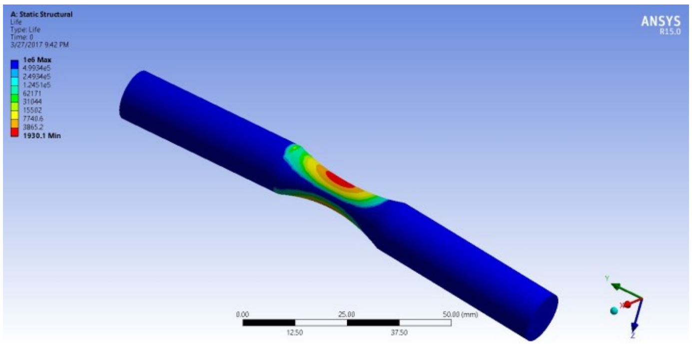

Fig 7: Fatigue life of E630 steel

IV. RESULTS AND DISCUSSIONS

Therefore, for the above combination of specimens, fatigue analysis is carried out by giving three different bending loads as shown in figure within the range of stress, and their corresponding number of cycles to failure is found out and the results are compared with conventional high strength steel.

TABLE II. NO OF CYCLES TO FAILURE AT THE STRESS OF $0.5\sigma_u$

S.No	Specimen ID	Specimens Name	No of Cycles in ANSYS	Percentage increase
1	HSS01	Conventional steel 1	10749	---
2	HSSG01	GFRP wrapping 1	13741	27.84
3	HSSGAl101	GFRP Al 1% wrapping 1	19496	81.38
4	HSSGAl301	GFRP Al 3% wrapping 1	18176	69.09
5	HSSGAl501	GFRP Al 5% wrapping 1	18214	69.45
6	HSSGTi101	GFRP TiO_2 1% wrapping 1	18136	68.72
7	HSSGTi301	GFRP TiO_2 3% wrapping 1	18770	74.622
8	HSSGTi501	GFRP TiO_2 5% wrapping 1	18465	71.782

For the minimum stress range of $0.5\sigma_u$, it is seen that minimum of 27.84% fatigue life of high strength steel is increased while using GFRP wrapping and maximum of 81.38% while using GFRP Al 1% wrapping when compared with conventional high strength steel.

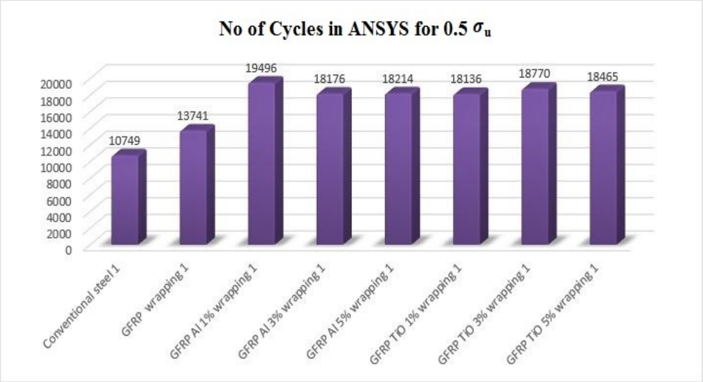

Fig 8: Comparison of fatigue life at $0.5\sigma_u$

TABLE III. NO OF CYCLES TO FAILURE AT THE STRESS OF $0.7\sigma_u$

S.No	Specimen ID	Specimens Name	No of Cycles in ANSYS	Percentage increase
1	HSS02	Conventional steel 2	5516.1	---
2	HSSG02	GFRP wrapping 2	6416.1	16.32
3	HSSGAl102	GFRP Al 1% wrapping 2	8147.2	47.70
4	HSSGAl302	GFRP Al 3% wrapping 2	7750	40.50
5	HSSGAl502	GFRP Al 5% wrapping 2	7761.2	40.70
6	HSSGTi102	GFRP TiO_2 1% wrapping 2	7738	40.28
7	HSSGTi302	GFRP TiO_2 3% wrapping 2	7928.7	43.74
8	HSSGTi502	GFRP TiO_2 5% wrapping 2	7836.9	42.08

For the medium stress range of $0.7\sigma_u$, it is seen that minimum of 16.32% fatigue life of high strength steel is increased while using GFRP wrapping and maximum of 47.70% fatigue life is increased by adding Al 1%.

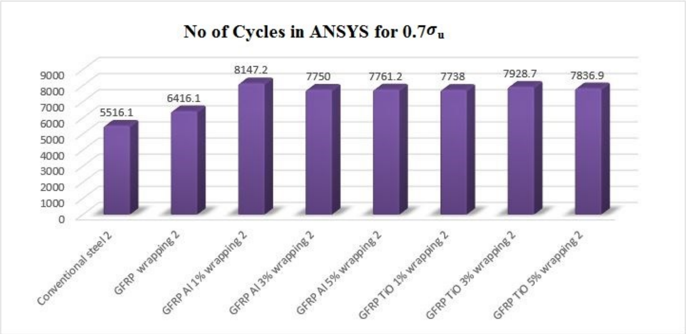

Fig 9 : Comparison of fatigue life at $0.7\sigma_u$

TABLE IV. NO OF CYCLES TO FAILURE AT THE STRESS OF $0.9\sigma_u$

S.No	Specimen ID	Specimens Name	No of Cycles in ANSYS	Percentage increase
1	HSS03	Conventional steel 3	1930.3	---
2	HSSG03	GFRP wrapping 3	2069.2	7.20
3	HSSGAl103	GFRP Al 1% wrapping 3	4292.3	122.36
4	HSSGAl303	GFRP Al 3% wrapping 3	3872	100.59
5	HSSGAl503	GFRP Al 5% wrapping 3	3797	96.71
6	HSSGTi103	GFRP TiO_2 1% wrapping 3	3766.7	95.14
7	HSSGTi303	GFRP TiO_2 3% wrapping 3	4011.7	107.81
8	HSSGTi503	GFRP TiO_2 5% wrapping 3	3893.8	101.72

For the stress range of $0.9\sigma_u$ GFRP wrapping with the Al 1% shows the better result.

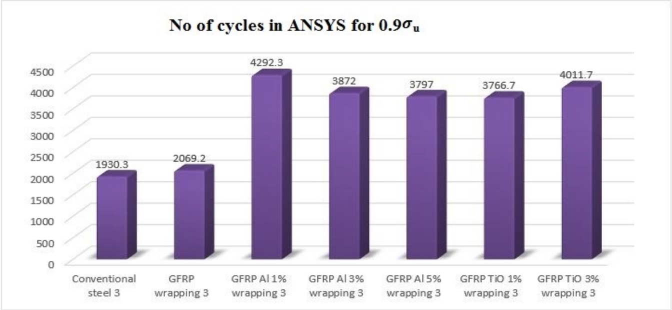

Fig 10 : Comparison of fatigue life at $0.9\sigma_u$

Fatigue Sensitivity:

Fatigue sensitivity is similar to the S-N curve which shows how the fatigue results change as a function of the loading at the critical location on the model as shown in the below chart.

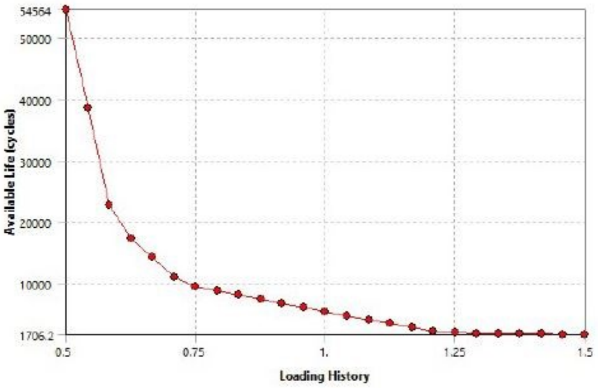

Fig 11 : Fatigue sensitivity curve for E630 steel

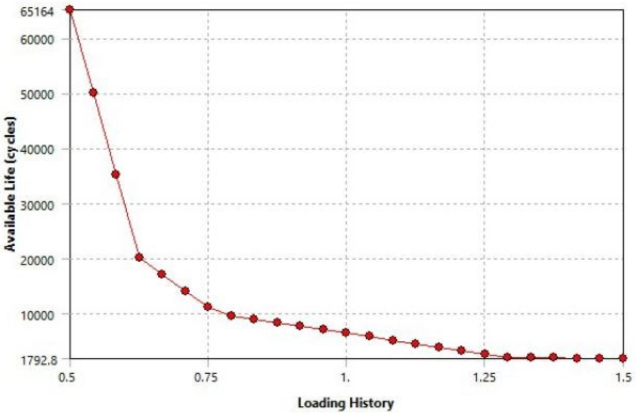

Fig 12 : Fatigue sensitivity curve for E630 steel with GFRP wrapped

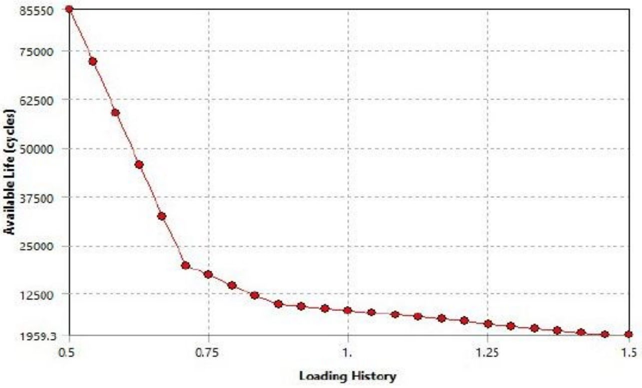

Fig 13 : Fatigue sensitivity curve for E630 steel with GFRP + Al 1% wrapped

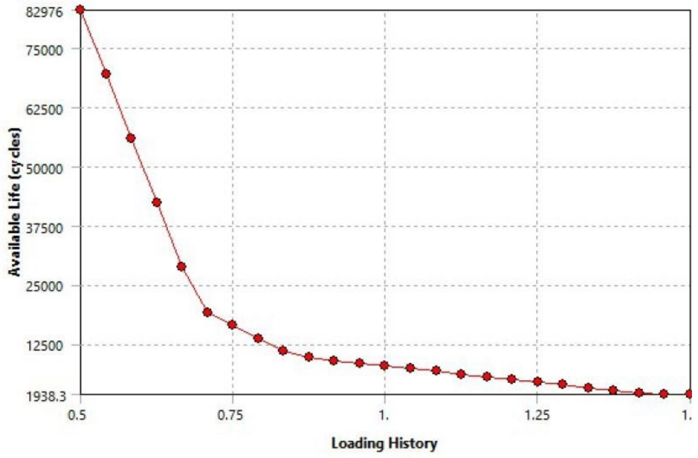

Fig 14 : Fatigue sensitivity curve for E630 steel with GFRP + TiO_2 3% wrapped.

V. CONCLUSION

Thus for the enhancement of fatigue strength in HSS, fatigue test is conducted on 8 combination of specimens, with and without varying percentage of Al and Tio_2. From this it is observed that, at the endurance limit,

- Among 1%, 3% and 5% of Aluminium filled GFRP combination, 1% of Al shows that increase in fatigue strength of 81.38% when compared with conventional HSS and 41.9% when compared to GFRP wrapped HSS.
- Among 1%, 3% and 5% of Titanium di oxide filled GFRP combination, 3% of TiO_2 shows that increase in fatigue strength of 74.62% when compared with conventional HSS and 36.6% when compared to GFRP wrapped HSS.
- Between Al and TiO_2, Al at 1% shows the better result to increase the fatigue strength of HSS.
- Therefore, it shows that Al and TiO_2 filler have the potential to enhance the fatigue strength of HSS.

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