Fatigue Damage on Steel Space Truss Systems

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ABSTRACT. *Searching of light, practical, fast and industrial solutions in structure technology produces the space truss systems. Space truss systems are formed by steel bars which are under axial tension or compression loads connected each other with nodes. These systems provide constructing wide span structures by light structural elements and also make buildings more powerful and useful. Space truss system elements must be dimensioned due to the loads they carry as dead, live, wind and earthquake loads. As other structural materials, space truss system materials which are subjected to cyclic loads can be damaged because of fatigue effect. And also if truss system is not protected from corrosion effect, the ratio of fatigue crack growth increases. In this paper; fatigue damage of a steel space truss system is studied under snow and thermal loads. Results are compared to four space truss systems which are collapsed from snow loads and it is seen that collapsing mechanism of these space truss systems and calculation results match. And also it is observed that; corrosion and structural irregularities are effective in failure of these systems. Precautions are given for preventing fatigue failure of space truss systems.*

INTRODUCTION

Gropius, the founder of Bauhaus, developed a bar-node system (now called as space truss system) and first truss system structures are made in 1942 by this way [1]. In a short time, space truss systems become a common method in big projects. The unit member of a space truss system has 6 bars and 4 nodes. This unit element can be replicated easily with 3 bars which are in different directions. Now as a common structural system; Truss systems are formed with tension-compression bars which are connected to each other by nodes. This systems transfer loads in two directions by using nodes as transfer gates. Space truss systems are mostly used in industrial buildings, malls, showrooms, exhibition centers and sport complexes (Ayhun 2006). With these systems long spans can be constructed with less columns and this provides a more useful structure. These systems are lighter than most structural systems. Because of earthquake loads increase proportional to the mass of the structure, space truss systems face with less lateral loads during earthquakes if they are compared to heavier systems. And also ductility and toughness values of these systems are greater then reinforced concrete systems. This proves truss systems a higher energy absorbing capacity. Wide spans can be constructed up to 150 m. by this method. Architectural needs also can be satisfied by constructing different space truss system forms (square, rectangle etc.). Also truss systems can be set in parabolic and dome shapes. Cables, funnels etc. can be easily placed into spaces formed between space truss system bars. Every geometrically defined system can be formed by space truss system. This means satisfying architectural needs in a safe way.

Lightest hyper static steel systems are space truss systems. Space truss systems are high-degree hyper static systems. As a reason of this; load of damaged structural element transferred to other elements and structural stability is protected. Also it is possible to replace damaged bar with a new element. Space truss elements are not under bending effects, so building safe and long spans with fewer columns is possible by space trusses. Space truss systems are deformed under different load combinations. In this paper; service life of space truss systems are studied under snow and cyclic thermal loads and corrosion effects. Because of stress distribution principles; space truss systems fail when a certain number of elements are failed.

FATIGUE

Fatigue is a terminology to describe the damage and failure of materials under cyclic loads in engineering applications (Fig. 1). Fatigue failures generally take place at a stress much lower than the ultimate strength of the material. The failure is due primarily to repeated stress from a maximum to a minimum. Fatigue failure may occur in many different forms such as mechanical fatigue when the components are under only fluctuating stress or strain; creep-fatigue when the components under cyclic loading at high temperature; thermo mechanical fatigue when both mechanical loading and temperature are cyclic; corrosion fatigue when the components under cyclic loading impose in the presence of a chemically aggressive environment. Many variables can influence corrosion fatigue crack growth. Many of the significant variables have been examined, and the results are available in a number of review papers.

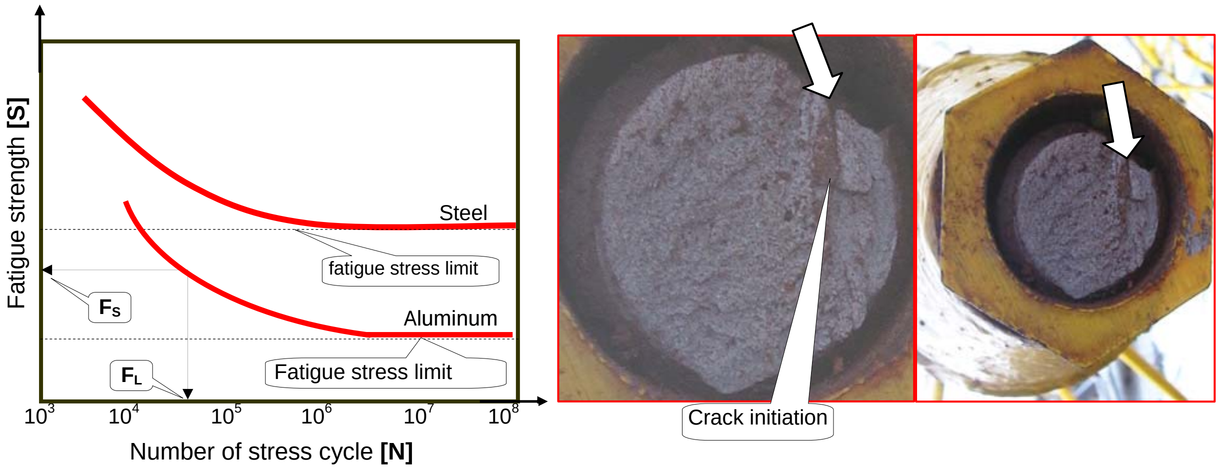

Fig. 1 S-N diagrams of Steel and Aluminum and fatigue failure

For some materials, the S-N curve becomes horizontal for big N values. The fatigue stress limit is maximum stress amplitude below which the material never fails, no matter how many the number of cycles is. Fatigue strength (F_s), stress at which fracture occurs after specified number of cycles. Fatigue life (F_L) is number of cycles to fail at specified stress level. Crack initiation at the sites of stress concentration (micro cracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important. Stage I, initial slow propagation along crystal planes with high resolved shear stress. Involves just a few grains, and has flat fracture surface. Stage II is faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip (Fig.2a).

Fatigue is damage of materials under cyclic loads. Fatigue failure generally occurs under a stress lower than the strength of mentioned material. Failure is basically formed by a cyclic loading between a max and min value. Waving stress and deformations cause mechanical fatigue (Fig.2b), Thermal stresses cause creep fatigue (Mäkeläinen 2003). Also earthquake loads cause fatigue too (Fig.2c)

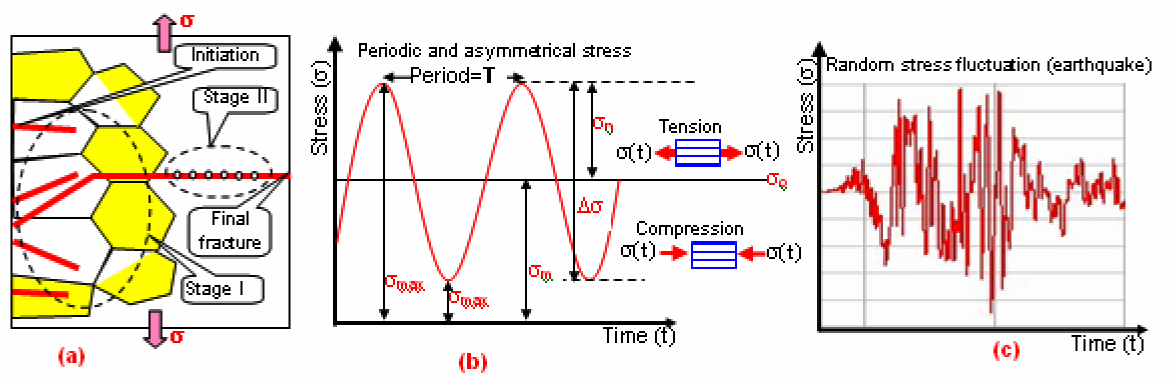

Fig. 2 (a) Fatigue mechanism (b) Terminology used in constant-amplitude loading (c)Variable-amplitude loading history

Following equation can be written if graph in Fig. 2 is examined (Eq. 1)

$$\begin{aligned} \Delta\sigma &= \sigma_{max} - \sigma_{min} \\ \sigma_m &= (\sigma_{max} + \sigma_{min})/2 \\ \sigma_n &= (\sigma_{max} - \sigma_{min})/2 \\ R_{(stress\ ratio)} &= \sigma_{min} / \sigma_{max} \end{aligned} \tag{1}$$

Earthquake loads can form cracks on elements of space truss systems because of high magnitude. These cracks increase damage ratio because of corrosion and fatigue.

CORROSION AND CORROSION FATIGUE

Corrosion is spoiling of a metal by environmental chemical or electro-chemical reactions. Corrosion is a common and expensive structural problem. Most serious result of corrosion is failure of a structural system. Failure can be occurred because of spoiling of structural materials (while they can not carry subjected loads) or cracks formed by corrosion. Corrosion types are; uniform or general, galvanic or two-metal, thermo galvanic, crevice, including deposit, pitting, intergranular and exfoliation, selective, erosion, cavitations, fretting, stress cracking and corrosion fatigue (Bardal, Drugli 2002). Corrosion fatigue is the environmentally-assisted mechanical degradation of a material due to the combined effects of corrosion and fatigue (a direct result of cyclic stress loading). It is often considered to be a subset of stress corrosion cracking (SCC), but the fracture mechanics and methods of prevention deviate enough from those of SCC that it warrants a separate discussion. Furthermore, Stress corrosion cracking occurs under static stress while corrosion fatigue occurs under a cyclic stress (part of which is tensile stress). Corrosion fatigue is a potential cause for the failure of many types of metals and alloys in various types of environments.

Materials that experience corrosion fatigue essentially exhibit a decrease in fatigue strength due to the effects of electrochemical degradation (corrosive environment). The stress required for both crack initiation and propagation is lower in corrosive environments. The crack growth rate can be much higher in a corrosive environment than it is in a non-corrosive environment. Therefore, the fatigue life of a material is shortened if it is simultaneously exposed to a corrosive environment and fatigue conditions. Like the general case of fatigue, corrosion fatigue cracking is often characterized by “beach marks” or striation patterns, which are perpendicular to the crack propagation direction. There are a number of factors that affect the onset of corrosion fatigue and the growth rate of cracks caused by this form of corrosion. For example, corrosion damage, such as pitting, causes stress raisers in the vicinity of the pit, much like notch effects. This can lead to crack initiation at a stress below that for a material in a non-corrosive environment. The crack will then propagate at a faster rate, as corrosive elements enter the crack. Temperature, metal composition, strength and fracture toughness are other examples of environmental and material factors that affect the occurrence and rate of corrosion fatigue (2).

The first trend to be noticed in corrosion-fatigue behavior is that the fatigue stress limit is observed when steel is fatigued in air is significantly lower or erased by a corrosive environment. Fig. 3. illustrates this general trend. As the figure illustrates, the fatigue strength of the metal in corrosive environment continues to fall as the cycles to failure is increased. It has been found that in most low-alloy steels fatigued in contact with salt solutions, there is no "safe stress range" at which the metal has infinite life (Eyins 2004).

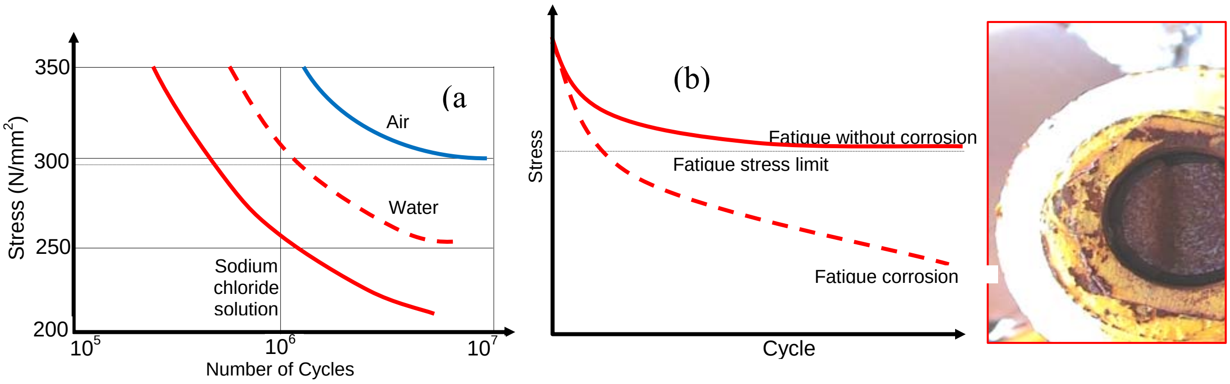

Fig. 3 Stress-Cycles (S-N) curve and corrosion fatigue

Corrosion fatigue describes the case of cracking of materials under cyclic loading in a proper environment (aqueous or gaseous). This is crack formation and growth by corrosion under simultaneous cycling stresses. Difference between corrosion and corrosion fatigue is; corrosion fatigue grows under cyclic loads. A surface corrosion case which may cause any type of corrosion can form corrosion fatigue. Fatigue; which formed in environments those are not proper for corrosion, have typical crack shapes. Corrosion fatigue has its own typical crack traces but it can not be clearly seen because of corrosion products (Fig. 4).

Fig. 4 Corrosion fatigue damage

Space truss system elements which are spoiled because of corrosion or pitting corrosion may fail because of their shrunk sections. Pitting corrosion occurs on more or less passivated metals and alloys in corrosive media containing chloride, bromide, iodide or perchlorate ions. So, shear strength of a structural element can decrease considerably and it can fail because of corrosion during time (Fig. 5).

Fig. 5 Shear fracture (corrosion)

The corrosion of the steel results in the formation of corrosion products, oxides and hydroxides, which have a greater volume than that of the original steel. Reduction in the cross-sectional area of steel reduces its strength capacity (Cosgun 2001). These corrosion products expand and exert internal stresses in the concrete leading to cracking and spelling of the concrete cover. Today, corrosion of steel reinforcement embedded in concrete is of a great socio-economic importance, with losses estimated to be in the tens of billions of US dollars per annum worldwide.

SNOW LOAD EFFECT

Snow loads forms thermal loads in addition to its own load. Design values of snow load are determined due to criteria given in codes. But sometimes buildings collapse because of extremely high snow loads. Snow load cases are seen in some structures (Fig. 6).

Fig. 6 Snow load on roofs

Sometimes snow loads will be more effective than other vertical loads. Every winter, buildings collapse because of snow loads all over the world and cause life and property loss. Especially steel or timber roof systems of big structures as hangar, sport complex, stadium etc. fails but snow load is not the only reason. Failed roofs have project and application mistakes. Snow load pulls the trigger. The most important parameters of snow load effect are geometry of the roof and direction of wind. Because of space truss systems are used in big structures, snow loads are effective in these systems. If the roof type is proper and the roof is perpendicular to the wind direction snow load effect is extremely increases. However if it's parallel to the wind direction snow loads won't be so effective. But although the wind direction is parallel to the roof side; melt snow can be fill the roof canals and increase the snow load. Roof system of Kurtulus Bazaar heavily damaged for this reason. Hidden roofs are always subjected to high snow loads and snow load value is independent from roof side and wind direction. Another problem in these types of roofs are collecting and freezing of melt snow in roof drains and increasing snow loads which may cause failure. Roof of stadium of a university heavily damaged because of this reason and thousands of buckled elements are replaced. If improper roof systems must be constructed, heating systems can be set under roofs and snow can be drained.

SOLVED MODEL

Space truss systems are high degree hyper static systems which are constructed with pipe elements those have hinges at nodes. In space truss systems; loads are transferred by nodes. Sections are dimensioned as compression-tension elements. Compression-tension capacity of an element must be chosen as the lowest value of; pipe galvanic hole section, weld, conic and bolt tension capacity. After analyzing the system for different loading cases, most critical loading is considered for fatigue analysis. For fatigue analysis; material types, loading case and effective loads must be known. In this study; space truss systems are studied so, structural elements are only subjected to axial loads. For this reason; only axial loading case is considered. Area of damaged sport complex is 28.80 x 43.68 m^2. Roof system elements are pipes in different sections, conics, bolts, nuts, nodes and spheres. Pipe ends are conics and bolts are connected to nuts with pins. Calculations are made under snow load and (200 kgf/m^2), thermal load (between $+25^o$ and -25^o). System is solved for two different cases. First, snow load is considered and in the second case, snow load is not considered. For both two cases max and min stresses are determined. These determined stresses are drawn on stress-strain diagram of St37 steel and average stress $(\sigma_1+\sigma_2)/2$ are found (Fig. 7). Maximum and minimum stress values of 10 truss system elements under similar loading are considered and average stresses are found for analysis.

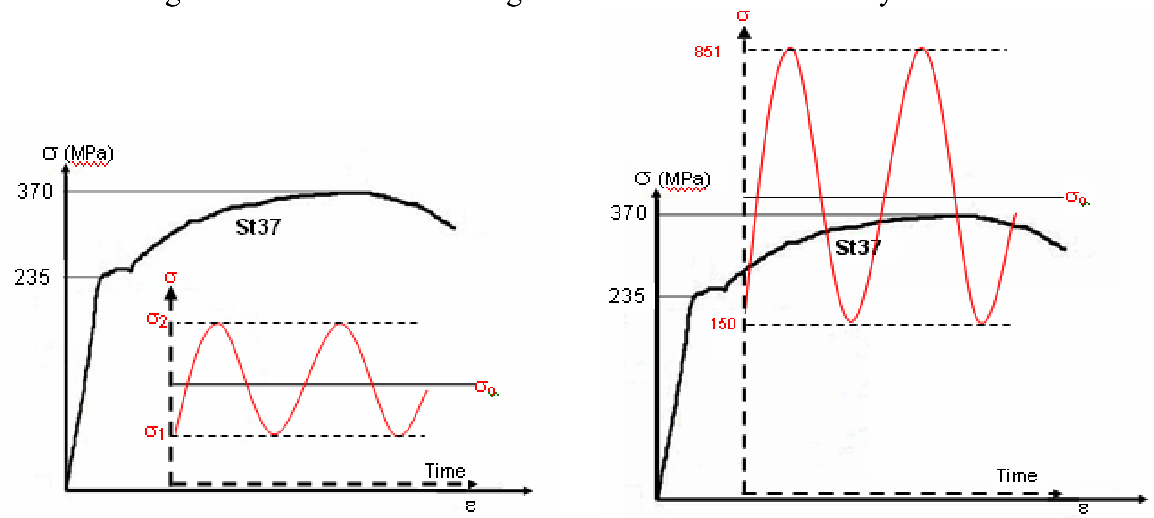

Fig. 7 St37 σ-ε curve and max-min stress values of the

If snow loads are not considered; $\sigma_1 = 117$, $\sigma_2 = 831$ and $\sigma_0 = (\sigma_1+\sigma_2)/2 = 474.00\ N/mm^2$
Snow loads are considered; $\sigma_1 = 150$, $\sigma_2 = 851$ and $\sigma_0 = (\sigma_1+\sigma_2)/2 = 500.05\ N/mm^2$
Values are plotted on S-N diagram of St37 steel and cycle counts are found (Fig. 8) (Guagliano, Riva, Guidetti 2002). System makes two cycles a day, so calculating the service life of structure will be easy. Service life of mentioned structural element is about 4.3 years if snow loads are considered (it is assumed that roof system is always subjected to snow loads). If snow loads are not considered service life increases to about 8.5 years. It is clear that; these values are proper if the construction date of structure is considered 1996.

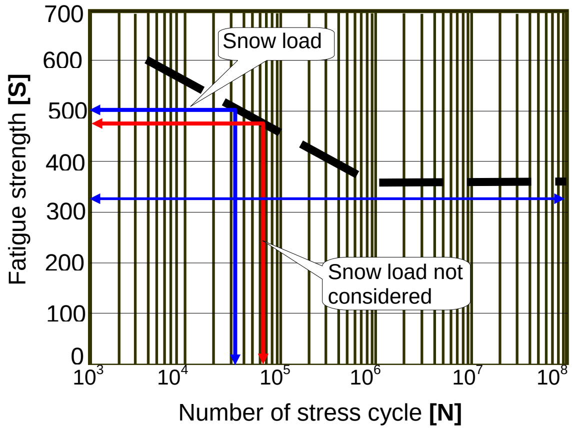

Fig. 8. St37 S-N curve

Because of low stress values of some structural elements, cycle number is found as infinite. This means these elements are not under fatigue effects. But also with effects as; corrosion, earthquake load etc. these elements can face with fatigue hazard. In solved system (Roof space truss system of Eskişehir Kilicoglu High school); pipes, conics and bolts are used. Specimens those taken from wreckage show that; internal reasons of failure are; corrosion fatigue, improper structural elements and assembly mistakes. External reasons are; temperature difference, snow load and service life limit. In other words; snow and thermal loads are not the only reasons of the failure, also structural and material irregularities were effective.

SPACE TRUSS SYSTEM IRREGULARITIES

In calculation of slenderity ratio of pipe elements, sphere axis distances must be taken in consideration. Also slenderity ration of bars mustn't be greater than the allowed values in codes. Pipes, bolts, spheres and conic diameters must be proper to the loads. This homogeneity must be provided in whole structural system. Irregularities on supports, nodes and element connection welds increase fatigue ratio. Welded structural elements mustn't be used because linearity of welded elements can not be provided so homogeneity lost in these types of elements. Strength of pipe section and weld are not the same. Weld thickness can not be thicker than the pipe thickness (a), peak value of weld thickness (t) must be limited according to the codes (for example; $a<=0.7t_{min}$). Pipe elements mustn't be welded, in other words two pipe sections mustn't be connected to each other by weld for producing a long pipe element (Topçu 2000). Otherwise damage will be certain in these types of elements. Because of other loads, fatigue stress values of the mentioned space truss system are increases. In static and dynamic calculations of structural systems, support rotations and displacements are effective too. These effects cause forming of greater stresses (Hibbeler 2003). In some damaged space truss systems, support irregularities are seen. These irregularities cause failure of the structural system. In space truss systems support connections must allow limited displacements because of thermal loads.

In nodes of space truss systems, growth and corrosion of micro cracks by time which are formed around bolts caused failure. This damages cause collapsing or/and increasing of fatigue speed of the system.

CONCLUSIONS

In designing of space truss systems, thermal conditions of the region which structure will be constructed must be considered. And also snow loads, material strength and seismic activity must be taken into consideration. Calculations show that; structural irregularities are also effective in failure of the space truss systems. Even it is seen that some elements are critically loaded by their own weight. In some elements fatigue age is infinite. System must be analyzed and designed well for not forming extreme conditions like this. If the structure is important, strain or stress gauges can be used for real-time tracking. For preventing fatigue in space truss systems;

- Internal temperature must not be increased too much if weather is too cold
- Preventing corrosion by a good upkeep
- Heating roofs for decreasing snow loads
- Not constructing hidden roofs
- Not constructing irregular elements, supports and nodes
- Setting roof slope proper to the wind direction

Precautions must be taken.

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