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An experimental study on the residual mechanical properties of structural steel members in an industrial warehouse following a fire incident

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ABSTRACT:

In this paper an experimental study on the fire damage of the unprotected structural steel members is presented after exposure to fire in an industrial fabric established for embellishment of glass wares in 1982. Following the ignited fire flashover occurred, and finally 4,000 m2 areas were heavily damaged. The structural bearing system of compartments was designed as moment-resistant frames having 11.80 m height. In some halls a space truss roof construction with steel bars which were joining in Mero type assemblies was pin-supported on the columns which were fix on their bottom. Steel columns were made from hot rolled I sections.

Tensile tests were performed on specimens taken from various columns and a tubular space truss member in order to determine post fire mechanical properties. Also, residual factors defined as the ratio of post fire mechanical properties to those at room temperature, and exposed temperatures of the samples were estimated by referring the results of a previous work in the literature. In this approximation, yield strength to ultimate tensile strength ratio of the samples subjected to controlled heating to and cooling from elevated temperatures in the previous work were taken as the reference, and the present results were evaluated based on those results.

All the findings obtained from this experimental study were used as a tool in order to get information about the hazard level which helped for final decision whether removal, reusage or strengthening of the structural steel bearing members might be needed for the compartments of the steel industrial plant exposed to fire hazard.

ARTICLE INFO:

Keywords: fire damage; mechanical properties; steel structure; warehouse.

1. Introduction

The steel discovery and creation induce a revolutionary leap in the construction industry, steel provides perfect elasticity until yielding, and carries great tensile as well as high compressive forces, which explain the great adoption of steel in the buildings industries. In worth to mention that the steel is expensive in the UAE regions due to its scarce, which limited it adoptions where only curtain structures are based on steel completely such as warehouses.

Wang, et al. (2013) asserted that the steel structure does not provides a significance or adequate resistance against fire condition due to the high thermal conductivity of steel, as well as the quick degradation of both steel strength and stiffness characteristics. Hence, the fire is considered as critical condition composes high temperate environment to the steel, based on witnessed of steel performance in major fire and explosion disasters, in which all safety measurements, such as fire alarm, were failed.

Through the history of the world, various fire disasters were registered, mentioned the Summerland Leisure Centre, 1973 (Rasbash, Ramachandran, et la, 2004, p: 35) , King's Cross Underground Station, London, 1987(Rasbash, Ramachandran, et la, 2004, p: 38)., Interstate Bank, Los Angeles, 1988 (Qiang & Guo, 2007).

In general, the steel in the high temperature condition, it elongates, in more scientific perception, this defined as the coefficient of linear expansion, and this coefficient asserted that the material length increased corresponding to increasing in the temperature, in similar, steel structure mechanism adopted same phenomenon in case of fire; When the steel beams are exposed to the fire it develops axial compressive forces inside the steel because of the thermal expansion. These two factors, the axial force and the applied force are considered widely during designing stage (Kodur & Dwaikat, 2008).

The beam capability of bearing and the internal force generation is based on the stress strain curves, Thermal expansion coefficient, and Thermal conductivity of the material. According to figure one, Steel structure undergoes a strength reduction of approximately 90 percent at temperatures above 800° C, while at 550 ºC, the yield strength of steel is degrade by half, while the yield strength is 10 percent or less at 1000 ºC, this emphasized the collapse phenomenon of the steel in the high temperature such as fire conditions.

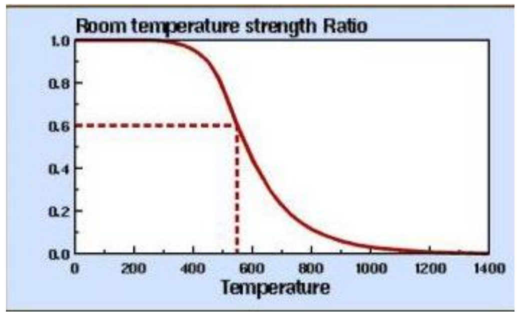

Figure 1. Strength Vs Tempreture (c)

The fire impact on the Steel features

For tested the fire impact on steel three parameters will be considered, which are : stress, strain, yield, and modulus of elasticity of the steel.

- Stress and strain: stress is the force applied loading on the cross section that leads steal o deform. Stress induced in case of load exerted on the material which cause deform of material which known as strain. In other engineering words, the strain defined as the size of deformation that caused due to the direct applied force divided the initial original length of the material resulting in a unit-less value of the strain.

- Yield strength is reflect the deformation type in steel, that provide an indication for the strength level on the steel sample, in which the steel strength decreased dramatically with the increasing of temperature as shown in figure 2.

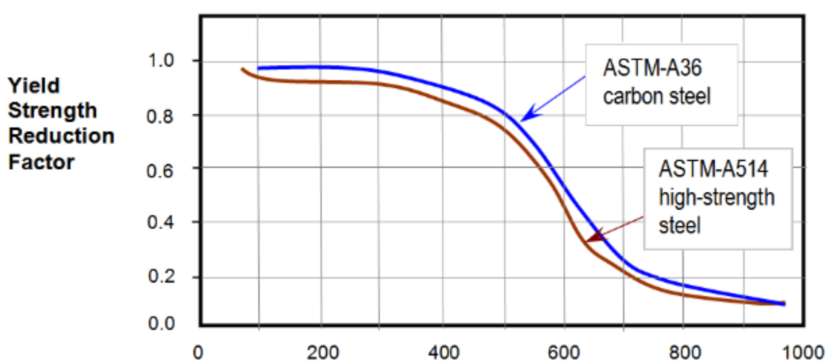

Figure 2 Reduction of Fy with temperature increase

Expansion of steel is primarily based on the temperature, as afore mentioned, the unstrained steel is elongates with the increasing of temperature, while the axially restrained steel cause a great compressive forces in the steel if the room is not considerable for unrestricted expansion, In this case, Buckling will probably occur with the increase in temperature above the 650-750°C range due to the reduction of the yield strength Fy and the modulus of elasticity E. Force transmission commonly occur as tension through the slab and compression through the steel joint, and stiffness generated on the other side of the connection, which maximize the moment transferred to the connection that indicate the semi rigid of the connection. Particularly, behavior in fire at the end of the beam is strongly restrained against elongation. Therefore, there will be tension again against the slab due to the stiffness of the beam. Figures 3 & 4 illustrate of recommended connection detail adopted fin plate connection on the side edge of the beam.

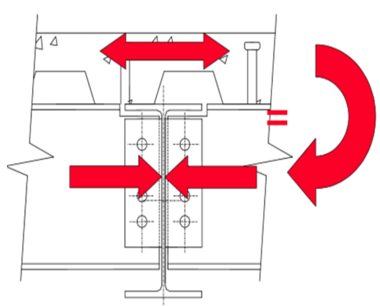

Figure 4.Internal connection detail at end of secondary beam

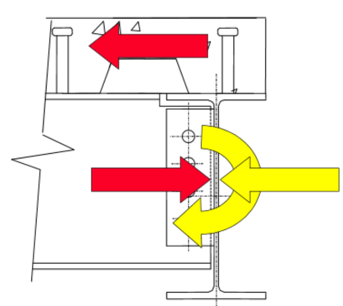

Figure 3 :External connection detail at end of secondary beam

. It is important to note that steel is weak when it is put in fire, hence it must be supported or covered with some other material to provide safety and more strength. For some cases several connections also used to provides the strength to the structure. Different experiments were conducted with several supports such as fixed support, point support, pin-pin support and fixed sliding support (Buchanan, Moss, et al, 2004).

In last few months, the fire accidents were significantly noticed in region that cost around millions of dollars loses in products as well as collapsed structure; therefore, the need for addressing steel behavior in the high temperature conditions was emerged, especially after looking through the major fire disasters, one can conclude that even in important and well-designed structures, the interior decoration can significantly affect the fire behavior. It is important to understand that if all safety measures fail, it is our responsibility as engineers to provide a structure that can sustain. The collapsed of steel within certain conditions is not an easy, ignorable problem since steel bound to fail if it exposure to high temperature and exposure time for it breach the thresholds. Therefore, the aim of the study is to study the high temperature effect on steel buildings, and analyze a burnt warehouse structures in Dubai.

The study has great significance providing that provides in-depth analysis and test of steel, that may reveal specific facts about the quality change of the steel in such conditions, indication the need for improvement to save a lot of lives, reduce the economical loses and reduce the effect on the environments, even that the fact of increasing the quality of steel will never prevent it from melting, but this improvement can increase the time period before steel melting, using the steel drastic deform as alarming sign, which increase the evacuation success potential for burnet buildings.

1. Experimental procedure

The following steps were followed to achieve study objectives:

- Review the literature which aims to build a strength background of the study topic, which qualitative and quantitative data obtained from AUS library database that contains various international journals and research data base in the field of the civil of Engineering. This procedure took one week to accomplish.

- Familiarizing with codes: in this study the AISC steel construction Manual is adopted as reference for steel structures, reviewing the code consumed two days.

- Site Visit: the study site is divided in three zones, coded 0,1,2 referred to the zone nearby to the origins of fire. Through site visited the authors take advantages of the assistance and recommendation provided by with Dr. Rami Haweeleh and Dr. Farid Abid , who are most familiars with the such kind of projects.

-Obtaining Architectural Plans : the architecture plan were acquired from the Site manager, the3D architectural model of structure and cross sectional was obtained.

-Obtaining Study sample form site, the sample were collected from site, form different three zones, and coded referred to the relevant zone code.

- Preparing the Samples: the preparing of the sample will be according to the ASTM E8 specification and standards, in order to guarantee the samples conformity with Coupon test machine, this procedure achieved by assistance of MR Ricardo De Jesus from Mechanical engineering department.

- Applying Test: the Coupon test were applied, on 6 samples taken from zone (0) (the closet area to the origin of fire), and three specimens from the other zones. The applied load is set as 100Kpa. This procedure took four weeks in order to have a valid parameters' reading and measurements for comparison purposes between zones.

-Analysis The result: the results contains information about load, deformation, then both strain and stress will be computed for each sample, in order to plot the stress-strain curve, and the load corresponding to deformation.

-Use Equations: this will be to calculate the modules of elasticity for each sample in the fire condition environment

-Comparing results: in this stage the results of modules elasticity for three zones will be compared to each other, in order to get the information about the steel behavior in each zone.

-Simulation of warehouse: this simulation the study adopted the SAAP program, in which the warehouse will be built, then the modules of elasticity measurements will be dropped on the steel member in the design of the warehouse, then the behavior will be observed.

- Summarizing findings: the final conclusion and results driven from study will be organized in a well-structured report.

The budget allocated for this study is estimated as 2000AED, which mainly used for strain gages purchases for satisfy tensile test requirement for samples. Furthermore, Coupon test machine is already available for us to use at the AUS Civil Engineering materials lab in order to determine the reduced strength of the steel samples due to the fire

The main resources of the study obtained from the following references and sources: Dubai police, AUS labs, and databases.

There are some limitations that accompany the analyses performed for this warehouse case. One of these limitations is using 800 C degrees as the highest temperature reached during the fire. Using 800 C degrees is based on the report from the police department; however this number is not exact as the police report doesn't specify exactly 800 C but a range of 700-800 C degrees. Therefore, one of the limitations is not to know the exact temperature degree reached under the fire situation in order to get the exact elasticity value under the fire.The second limitation is the simplified equation used in calculation the Modulus of Elasticity of steel during the fire and under the 800 C degrees; however, these equations do not include any parameters that specify the exposure time to fire. If it exists, this would really show gradual decrease in the elasticity and ultimate strength continuing in time until reaching the 800 C degrees, instead of only knowing the final results under the maximum temperature reached.

Before getting the result, it is worth to mention the sample preparation. According to requirement of using the Coupon test, the samples need to be shaped. For achieving the shape measurement the samples were cutting in the mechanical lab, as specification illustrates in the figure below. In Protrusions and projections either due to the fire deflection or due to the cutting process, therefore, special machine from the mechanical lab were used to get rid of any unnecessary parts

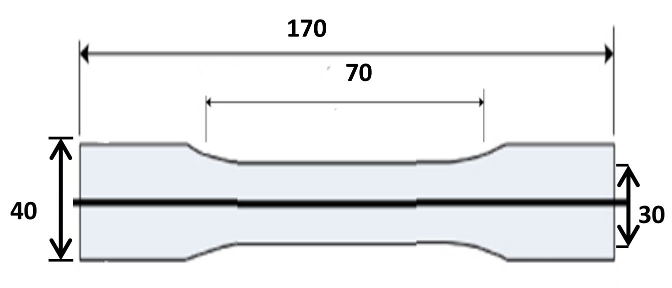

Figure 5 ASTM A1067 -Standarded specification of sample **Figure 6. Test Specimen**

Before adopting the test, the measurement of the specimen, such as width, thickness, and length of each specimen before deflection that will occur in the test, were taken using Vernier caliper, at three different points to find the thickness and the width, then at the end one average number calculated as the value of parameters.

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Furthermore, the sample is burnet, thus there is a need for preparing the sample for strain gauges, for example there is a need for rid the rusted damaged part of the steel surface in order to enable stick sensor wired on the sample (strain gauges). Special kinds of unsticking plastic papers have been used as base in order to apply cement glue on the sensors then stick it into the specimen after cleaning the specimen with thinner in order to make sure it is clean.

Figure 7.Cement glue andstrain gauges

2. Experimental results

The results of this experiment are based on the stress-strain curves in order to examine the behavior of the burnt steel. Furthermore, to come up with comparisons between the three zones along the warehouse that varies in the fire exposure duration and temperature according to the location away from the starting point of the fire.

It is important to know the stress and corresponding strain in order to enable predicting the strength capacity of the steel sample under a specific loading. There is a critical stress called the yield strength. This is a point where we can decide whether the deformation of steel is temporary or permanent, so it is considered an elastic limit. Specifically, if the material is loaded beyond this elastic limit, it will remain in a deformed condition after removing the load, and this is called plastic deformation. Moreover, at acceptable temperature, steel has well-defined yield strength; however, at high temperatures the yield point is not well defined anymore. So an estimation of the yield strength were used that is taken at the maximum point directly after the linear portion of the stress strain curve, (the elastic limit). As shown in figure no.8.

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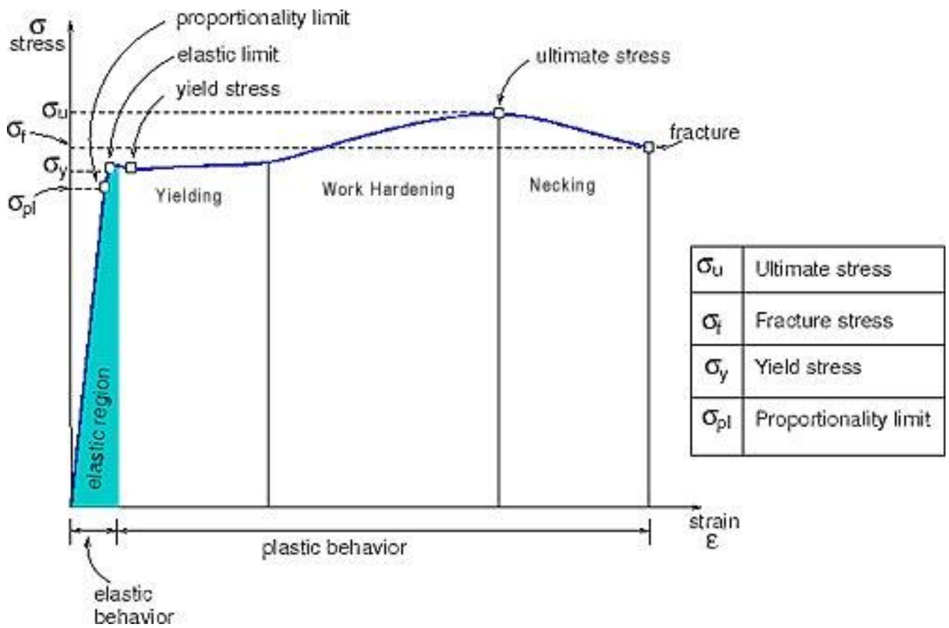

Figure 8. Yield Point (Elastic Limit)

Zones Results

After that the stress and the strain of the sample was calculated and a graph of the Load Vs. extension and Stress-Strain curve were plotted. Finally using the slop of the stress-Strain curve the Elasticity of the sample was obtained and the Elasticity during the fire was calculated using defined equation**.**

As result of the increase of temperature, yield strength and Young's Modulus of Elasticity E of the steel sample is decreased due to thermal expansion and contraction. Which this explaining the Zone 2 samples results and behaviors, which is the farthest one, which indicates the it was subjected to the least heat comparing to the other two zones, then the zone no.1 followed, and at last zone No.0. thus, the modulus of elasticity (E) assumed in zone 2 to be representative of yield of 200 Gpa and compare with the other two zones.

The samples of zone 2 taking a very long time before failure, also, majority of the samples didn't even fail and the load became constant. And majority of it consumed 10 to 15 minutes without failing. In contrary, the zero zone samples were failed within short time period, which indicate that the samples from zone two are much stronger than the capacity of the machine used which tells us that the specimens from this zone are relatively stronger than the other samples from the other zones. As shown in the following graph.

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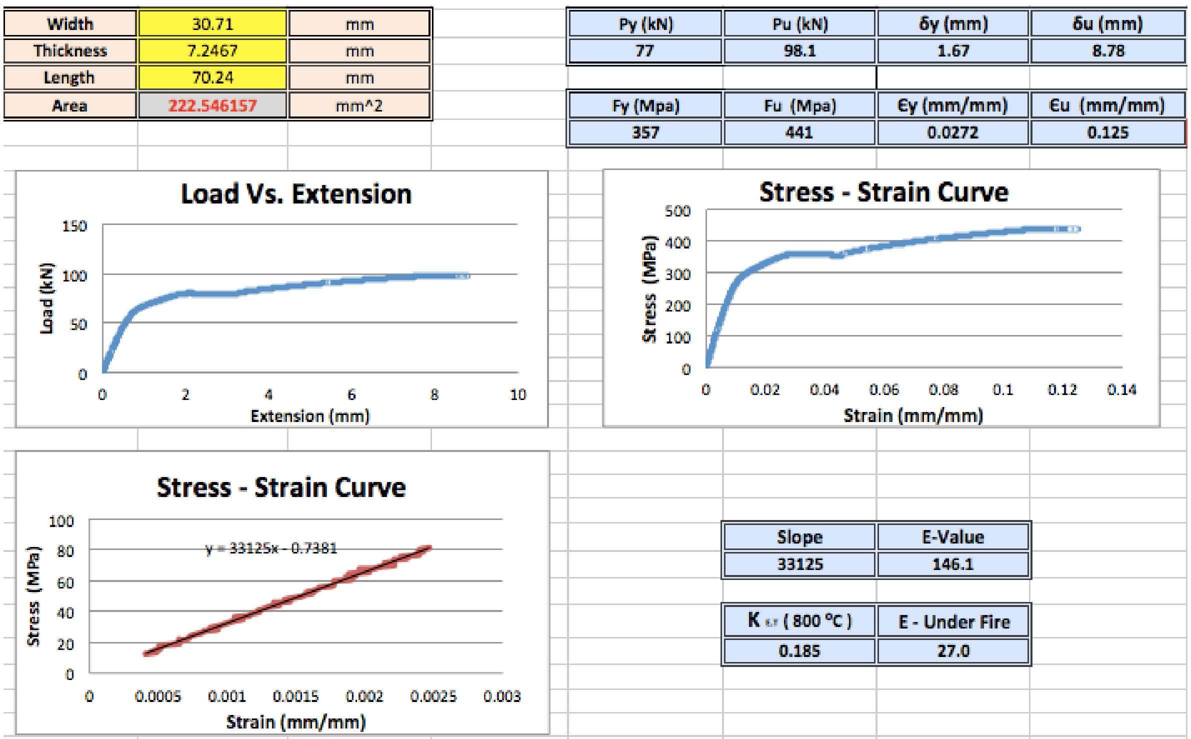

Width	30.71	mm
Thickness	7.2467	mm
Length	70.24	mm
Area	222.546157	mm^2

Py (kN)	Pu (kN)	δy (mm)	δu (mm)
77	98.1	1.67	8.78

Fy (Mpa)	Fu (Mpa)	Ɛy (mm/mm)	Ɛu (mm/mm)
357	441	0.0272	0.125

Slope	E-Value
33125	146.1

K (800 °C)	E - Under Fire
0.185	27.0

Figure 9.zone 2 non-failed sample

The obtained results emphasized that each sample has it highest Elasticity in the Web then in the top flange and finally in the bottom flange, as well as the Elasticity increased by being far from the fire started point. While comparing our values to a normal steel sample we will find that our result will be less than result of the normal steel sample because steel loses some of its properties if it got affected by high temperatures so you can see all the elasticity values they are all less than 200 GPa. Furthermore, the values of the ultimate stress and the yield stress found to be highest in the web section followed by the top flange then the bottom flange.

Zones Comparison:

The warehouse examined in three zones of analysis, as shown in figure below, the plan view of zones site in the ware house, tracking the start point of the fire which represented in zone zero, then expanded to zone one and then to zone two. There are walls separations between the zones, this helps the data resulted to be more accurate, thus the properties of the steel will varies between zones, and the differences in effect degree is also will be observed in reality, as shown in figure 11 below.

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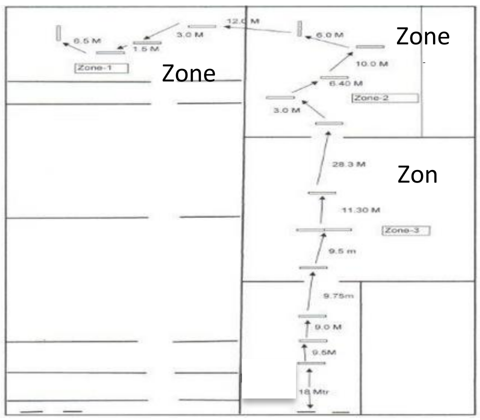

Figure 11. Collapsing in Zone zero Vs Zone

According to results shown in table no.1, the Modulus of elasticity is decreasing as become closing to the fire start point (origin) which reflect the strength decreasing in zone zero, which explained due to the higher temperature in zone zero compared to the other two zones, as well as the exposure duration for fire is longer to other two zones.

Table 1. modulus of elasticity of Top Flang- Web- Bottom Flang

Top Flange	ZONE	Modulus of elasticity
	2	154.6

	1	154.2
	0	144.9

Web	ZONE	Modulus of elasticity
	2	192.9
	1	187.4
	0	187.7

Bottom Flange	ZONE	Modulus of elasticity
	2	150.5
	1	140.3
	0	133.3

it is noticed that there are difference in results among top flange, web , and bottom flange in the same sample in terms of the resulting strength. Specifically, for zone 1 the strength has reduced from the 154.2 in the top flange to 140.3 in the bottom flange. the way the I-section beam is located indicates that bottom flange is exposed to the interior of the building where the fire occurred. This explains why the bottom flange has lower strength, and this is due to more severe exposure to fire. While the web is the strongest part compared to three parts of beam, which is reasoning due to vertical orientation of the web which support reduction the surface area that are subjected to fire, also, the web is placed between two flanges makes it harder for the heat to get to the web because the flanges will tend to absorb it first before transferring it to the web.

Figure no.12, summarize the comparison between three zones in terms of modulus of elasticity, proved that the zones that was subjected to more temperature and duration of fire experience more strength reduction, Further, the graph that the bottom flange has the lower strength; verified the explained the afore results.

Normalized Elastisity and Ultimate Stress

In summary, the average elasticity value for zone 0 is **155.3** and the average for zone 1 is **160.6**, however; zone 2 represents an average of **166.0**. On the other hand, discussion about the maximum value of elasticity and ultimate stress will be comparing three representative samples from each his zone. It can be observed that the three samples that have the maximum **Ultimate Strength** value are highlighted in each zone.

presents a comparison between the 3 different zones in terms of ultimate stress. It illustrates the normalized ultimate stress of steel and shows how it's greatly affected by that the increase in temperature. The sample that gives the maximum ultimate stress value was chosen from each zone in order to see the maximum difference in value between each zone. Shape-wise, it is obvious that the ultimate stress of representative sample from zone 2 is much higher than those from zone 1 and zone 0 and this is shown by the line falling drastically towards zone 0

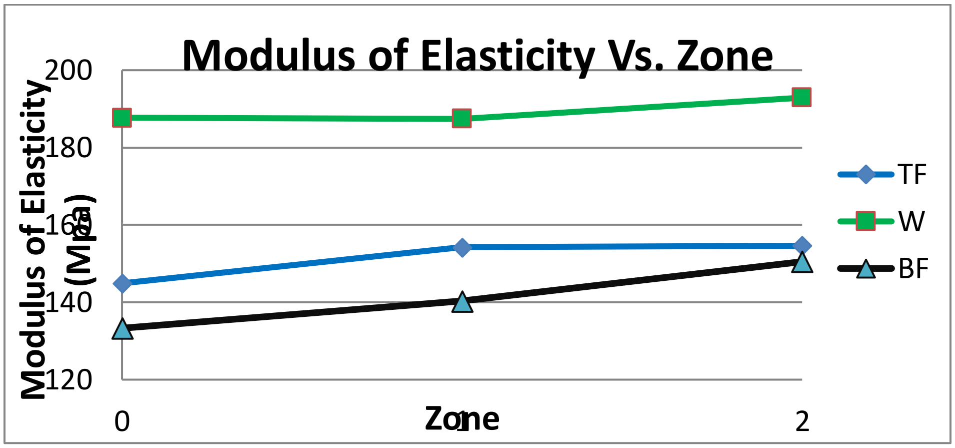

Figure 12. Modulus of elasticity Vs. Zone

The sample that gives the maximum ultimate stress value was chosen from each zone in order to see the maximum difference in value between each zone. According to the table no.2, . ultimate stress of representative sample from zone 2 is much higher than those from zone 1 and zone 0 and this is shown by the line falling drastically towards zone 0. As percentages, the ultimate stress in zone 1 was roughly 89% less than the ult. stress in zone 2, and about 66% less in zone 0.

Table 2. Ultimate stress and normlized stress

Zone	Ultimate Stress	Normalized Stress
2	499.5	1
1	442.7	0.89
0	430.64	0.86

For zone two we got the normalized elasticity to be equal to 1 cause the elasticity of that zone is 200 for zone two the normalized elasticity is 0.6443 which tells us that the elasticity of zone one is 64% of the elasticity of zone two and finally for zone zero we found that the normalized elasticity is 0.5656 and that means that zone zero elasticity is only 0.5656 of zone two elasticity which is almost the half of that elasticity and that shows how much the elasticity of the steel can drop during high temperatures.

ZONE 0

Fy (Mpa)	Fu (Mpa)
205.71	430.64

Ɛy (mm/mm)	Ɛu (mm/mm)
0.0110	0.159

ZONE 1

Fy (Mpa)	Fu (Mpa)
231.08	442.7

Ɛy (mm/mm)	Ɛu (mm/mm)
0.01233	0.238

ZONE 2

Fy (Mpa)	Fu (Mpa)
354.9	499.5

Ɛy (mm/mm)	Ɛu (mm/mm)
0.028	0.122

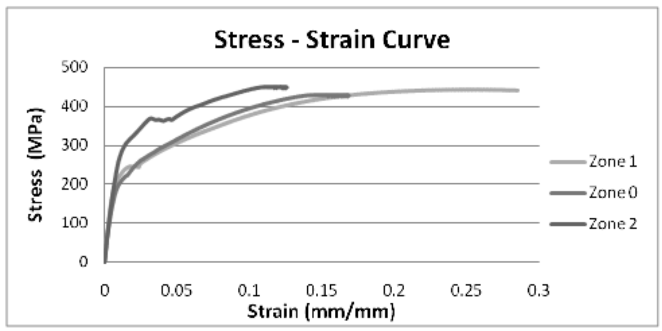

Figure 13. Stress-strain curve for each zone

After calculating stress and strain for each sample we found that zone two have the max ultimate stress and also it has the max yield stress. All of this reinforces our conclusion that by high temperature the behavior of steel changes and the stress that a sample from zone two can take a sample from zone zero will break if it was applied on the sample. The results between zone zero and zone one are close to each other however between zone one and zone two the gap is bigger and that shows that the temperature in zone zero and one are almost the same but the temperature of the fire has dropped in zone two. The graph shows the stress-strain curve for each zone, the highest curve corresponding to the highest stress which is in zone two followed by zone one then zone zero which has the lowest stress.

Modulus of Elasticity Calculations:

The modulus of elasticity during the effect of high temperature is calculated using this equation:

$$K_{E.T} = 1.0 + T / [\,2000 \ln (T/1100)] \qquad 0 < T < 600\ C$$

$$K_{E.T} = 690\ (1 - T / 1000) / (T - 53.5) \qquad 600 < T < 1000\ C$$

AND

$$K_{UNDER\ FIRE} = K_{E.T} \times E_{RISDUAL}$$

The equation includes the temperature degree parameter to be input which will result in giving a percentage of the elasticity to the residual elasticity value. According to the police report a value of 800 C degrees was used as the highest temperature reached and this resulted in ($\mathbf{K_{E.T} = 0.185}$) a percentage value of 0.185 E (18.5% Of Residual Elasticity).

$$K_{UNDER\ FIRE} = 0.185 \times E_{RISDUAL}$$

Warehouse design

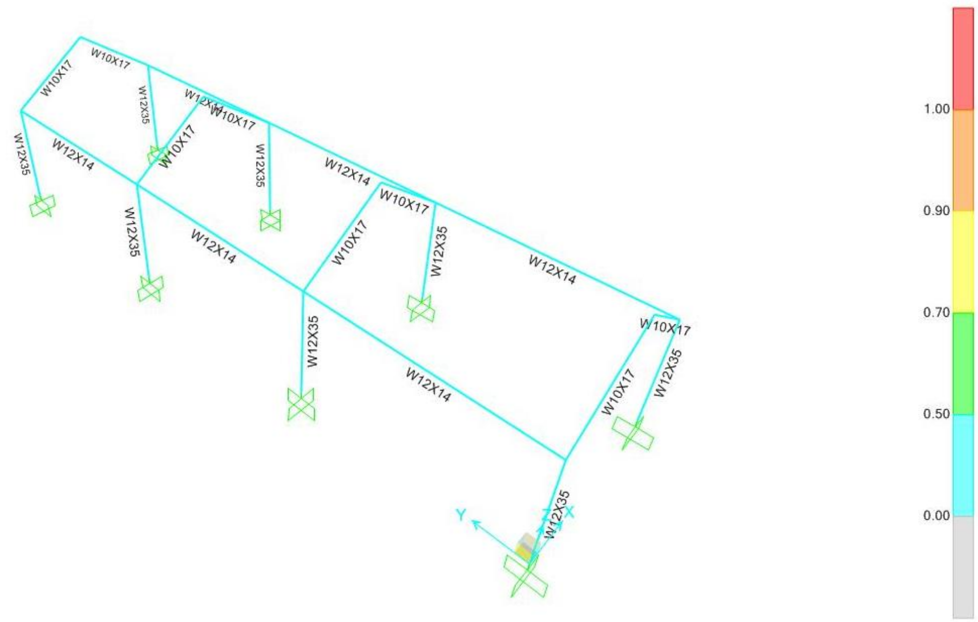

Figure 14. Design of warehose

This design is simulated using ETabs to illustrate the failure member due to the fire, which designed based on representative warehouse using steel sections with elasticity value of 200 GPA.

For presentation purposes, in order to show the failure in the sections of zone 0, we used the lowest elasticity value calculated in zone 0 where the fire started in the same design which resulted in great changes in the section safety indicator to show that these sections are to be not practical anymore as represented in figure 14.

It can be noticed that the design failed in some of the members highlighted in RED color. This red color represents failure in the members in other words raching Elasticity value of almost 30 GPa during and under the fire will result in failure and collapse in the members. In Figure 16, it shows that the deformation in the members during the fire in which resulted in full collapse in the upper members. So this representative design is just to show the failure of the warehouse and to highlight the members where the failure started since this is the exact situation happened in zone ZEOR in the warehouse, it was partially collapsed and a total mess.

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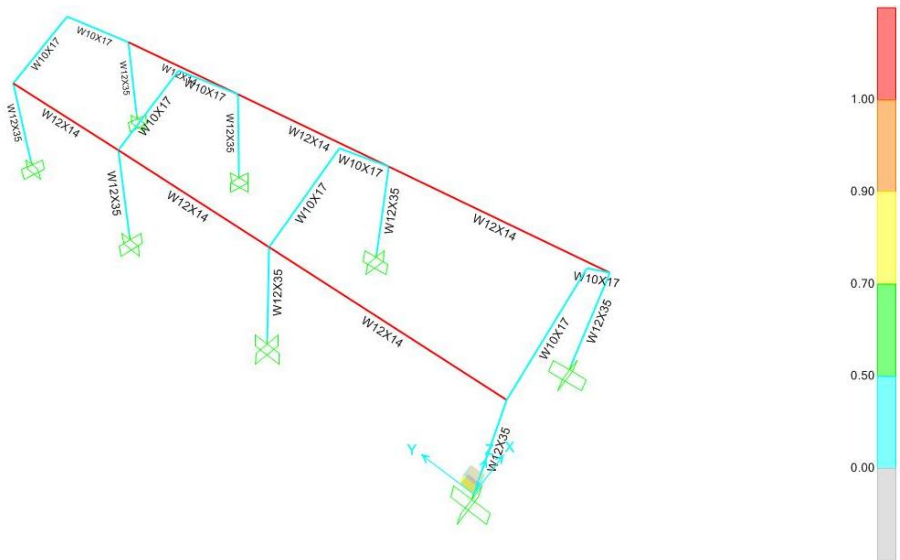

Figure 15.design of the wear house with low elasticity value

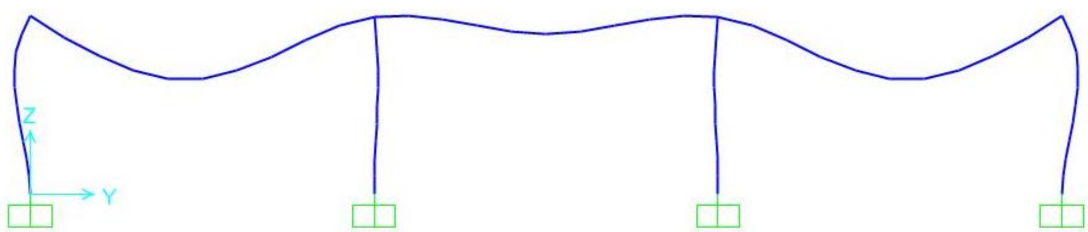

Figure 16: deformation of steel members

Conclusion and recommendations

After conducting the test on all the samples and calculating all the results we found in an I-beam will have the max stress and the max elasticity section in the web flowing by the top flange then the bottom flange. Also we found in the zones that zone two have the highest elasticity and the highest stress flowing by zone one then zone zero. Our elasticity value for zone zero the elasticity equal to 56% of zone two and it dropped to 10% of its real elasticity during the fire, for zone one is 65% of the elasticity in zone two after cooling and it dropped to 12.8% of its real elasticity under the fire and finally zone two dropped to 13.1% of its real elasticity during fire.

Since there were some limitations in this project, this section provide recommendations for future work.

- This project only investigated the collapse of the steel structure from the strength point of view. It is recommended to look at different causes of structure failure under the fire such as thermal expansion and creep.

- This project investigated the steel samples assuming that the temperature was uniform within each small member. Although many samples from different zone were taken in order to get the maximum reachable accurate result, however, advanced investigations could involve full heat transfer when the steel structure is subjected to ASTM E-199 standards fire. These kinds of investigations could involve the use of modeling in finite element software program which will be able to compute advanced heat transfer.

Acknowledgments

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