Behavioral Analysis of Hydraulically Driven Fire Fighting Water Monitor Trailer

Prashant S. Kadu
Department of Mechanical Engineeering
GHRCE, Digdoh Hills, Nagpur, India

Amit R. Bhende
Department of Mechanical Engineering
NYSS CER, Wanadongri, Nagpur, India

Abstract

In case of fire hazards, it is observed that a large amount of time is required to extinguish fire due to long distance between the place of the fire point and water monitor. This leads to wastage of huge amount of water. It is impossible to take water monitor closer to fire point because of high temperature. Hence, the fire fighting efficiency is very less, as it requires delivery of water at right time, right place and in adequate quantity. To reduce the distance between water monitor and place of the fire, a new fire fighting water trailer is developed by the authors. The trailer uses pressurized water to move forward taking into account the property like straitening, elongation and buckling of hose. When the water is pumped, then the pushing force is developed due to straightening property of the fire hose. This helps in taking the trailer closer to the fire point. This paper presents the study of behavior of the trailer material subjected to high temperature. The response of the trailer, which includes stress distribution and displacements under various loading conditions are analyzed in this paper. The method used in the numerical analysis is finite element technique using Ansys software. The results are presented and it shows that the stresses developed lies within the range and ensure infinite life. Methods of protection of the steel are also suggested to increase the efficiency of the trailer.

Keywords
Water monitor trailer, fire, Finite element model, stress distribution, deformation pattern, fire resistant steel.

1. Introduction

The strength of all engineering material reduces as their temperature increases. Steel is no exception. However, a major advantage of steel is that it is incombustible and it can fully recover its strength following a fire, most of the times. During fire, steel absorbs a significant amount of thermal energy. Steel returns to its stable condition on cooling at ambient temperature. During this cycle of heating and cooling, individual steel members may become slightly bend or damaged, generally without affecting the stability of the whole trailer. Using the principle "if the member is straight after exposure to fire- steel is OK", many steel members could be left undisturbed for the rest of their service life. Steel members which have slight distortion may be made dimensionally reusable by simple straightening methods and the member may be made put to continued use with full expectancy of performance with its specified mechanical properties. However it is useful to know the behavior of steel at higher temperature and methods available to protect it from damage done by fire.

2. Fire

Temperature is an intensive property, it means that it does not vary with the quantity of the material, while the heat is an extensive property, which varies with material volume. The two quantities are related through the heat capacity and the density. Burning hydrocarbon (jet fuel) using pure oxygen may reach approximately 3000º C, the same material burning in air produces about one third of heat that is 1000 º C. Thus the temperature experienced by steel as a result of the fire may be in the range of 750º C to 800º C, which is not sufficient to melt the steel. Typical value of melting temperature of steel is 1400º C to 1500º C.

To estimate the average temperature rise in hot gas layer space can be calculated as

$$\Delta T = \frac{220}{1 + 39.8\left\{\frac{Z^{5/3}}{Q^{2/3}}\right\}}$$

Where Z = Distance from fire source, m
Q = Heat release rate of fire, KW
ΔT= Average temperature rise, °C

$$Q = m\Delta H$$

Where M = mass loss rate, kg/s
ΔH= Heat of combustion, KJ/kg

3. Mechanical Properties of Steel at Elevated Temperature

Steel subjected to high temperature undergoes a substantial loss of strength and stiffness at a temperature far below the melting temperature, which is referred to as thermal softening and thermal damage, respectively. By loss of stiffness (thermal damage), we actually mean an increase of the deformability of the material under load. Figure 1 shows the relative strength and stiffness degradation with respect to increasing temperature. At a temperature level of about 600º to 700º C, which corresponds roughly to one half of the melting temperature of steel, strength and stiffness of steel are reduced to 50% and 30% respectively. Study about the mechanical properties of steel at elevated temperature is essential in case of fire resistant design of structural steel work. The variations of the non-dimensional modulus of elasticity, yield strength and coefficient of thermal expansion with respect to temperature are shown in figure-1.

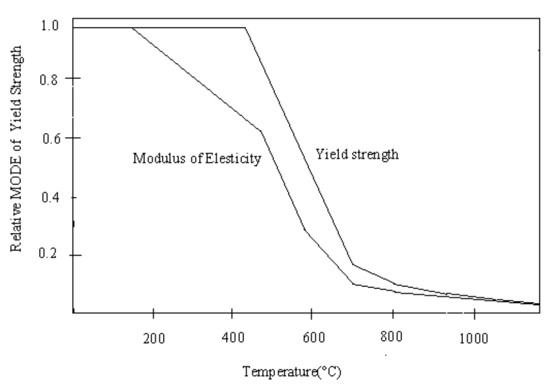

Figure 1: Reduction in properties of steel as a function of temperature

The corresponding equations are given below. The variation of modulus of elasticity ratio E with respect to the corresponding value at 20º C, with respect to temperature is given by

$$E = \frac{E(T)}{E(20°C)} = 1.0 + \frac{T}{2000\ln\left[\frac{T}{1100}\right]} \quad \text{for } 0º\text{ C} < T < 600º\text{ C} \qquad = \frac{690\left(1.0 - \frac{T}{1000}\right)}{T - 53.5} \quad \text{for } 600º\text{C} < T < 1000º\text{ C}$$

The yield stress of steel remains unchanged up to a temperature of about 500º C and then loses its strength gradually. The yield stress ratio f (with respect to yield stress at 20° C) vs temperature relation is given by

$$f = \frac{f_y(T)}{f_y(20)} = 1.0 \quad \text{for } 0º < T < 215º\text{ C} \qquad = \frac{905 - T}{690} \quad \text{for } 215º\text{ C} < T < 905º\text{ C}$$

Similarly coefficient of thermal expansion also varies with temperature by a simple relation

$$\alpha(T) = \left(12.0 + \frac{T}{100}\right) \times 10^{-6} \left(°C\right)^{-1}$$

These equations are very useful for the analysis of steel structure subjected to fire.

5. Water Monitor Trailer

The trailer used for the study has a gross weight of 85 kg. It consists of 25X25 angles as shown in figure 2. There are some additional members which are flat, bush, bearing, shaft etc. Towards the middle of the trailer, a wheel is provided for winding the fire hosepipe. This wheel is mounted on the shaft. The wheel can be adjusted on the shaft with the help of grub screw provided in the hub. Fire hose is allowed to pass through the rollers provided on the back side of the trailer. The top roller is fixed while the bottom roller is spring loaded to allow the elongation of the hose pipe after the movement of the trailer has stopped. The material of the trailer is mild steel with quenched and heat treatment. The properties of the material are shown in Table-1.

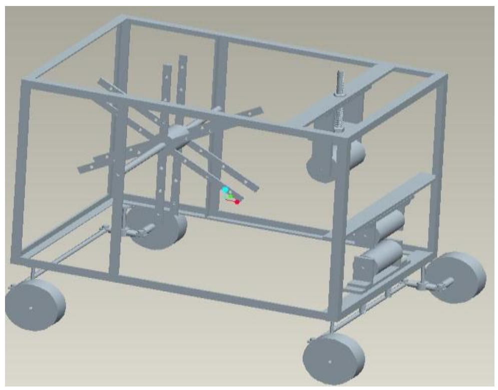

Figure 2: Trailer model

Table 1: Material properties at 20º C

Sr. No.	Name of Property	Value
1	Comp Ultimat Strength	0.0 Pa
2	Comp Yield Strength	2.5 x 108 Pa
3	Density	7850.0 kg/m3
4	Ductility	0.2
5	Poisson’s Ratio	0.3
6	Tensile Yield Strength	2.5 x 108 Pa
7	Tensile Ult Strength	4.6 x 108 Pa
8	Young’s Modulus	2.0 x 1011 Pa
9	Thermal Expansion	1.2 x 10-5 1/ ºC
10	Specific Heat	434.0 J/kg ºC
11	Relative Permeability	10,000.0
12	Resistivity	1.7 x 10-7 Ohm-m

6. Finite Element Model

The water monitor trailer is modeled by 10 node tetrahedral (Tet-10) solid92 element. Linear static analysis is carried on the model to find out the stress distribution and deformation pattern of the trailer under static loading. The trailer model is meshed with 8035 Tet-10 elements with 21175 nodes are used. The frame is treated as a simply supported beam and force exerted by the pressurized water due to sudden contraction in the hose pipe just before the rollers and the weight of the component applied to the beam were treated as the loading conditions for the trailer. The stability of the trailer is determined by finding out the normal reactions at various supports. The bottom spring loaded roller is allowed to have one degree of freedom in downward direction for compensating the compression of the spring. Loading conditions are defined by applying surface forces of magnitude 507.39 N each on top and bottom rollers and vertical load of 507.39 N on top roller.

7. Results of Static Thermal Analysis

Solution contains calculated response for the model under given loading condition at various temperatures defined in environment. The values of modulus of elasticity and yield strength of the structural steel are calculated at various temperatures with the help of equation given above. These values are used for the analysis of the trailer. Table2 shows the change in material properties such as modulus of elasticity, yield strength, displacement and coefficient of thermal expansion at various temperatures. Figure 3 shows the result of von mises stress distribution contour of the trailer under loading condition. The stress distribution is almost uniform, with highest stressed area at the bottom roller suspension springs, where the maximum stress is about 1.404 x 10^8 Pa. The rest of the trailer structure has very low stress value, about 2.71 x 10^{-3} Pa. Figure 4 shows the deformation contour and deformation pattern of the trailer under static load. The highest deformation happens at the top surface of the bottom roller where the hydraulic pressure is being applied. The maximum translation is 0.28 mm at 600° C. The deformation of the cross member and mounting bracket is low.

Table 2: Properties at various temperatures

Temp (T) °C	Modulus of Elasticity E(T), x 10^9 Pa	Yield Strength, Pa x 10^8	Coeff of thermal expansion x 10^{-5} 1/°C	Displa-cement, mm
50	205.32	2.5	1.2	0.142
100	202.68	2.5	1.25	0.1445
200	194.85	2.5	1.3	0.1505
300	183.10	2.19	1.4	0.159
400	166.07	1.82	1.5	0.176
500	141.36	1.46	1.6	0.207
600	104.54	1.10	1.7	0.280

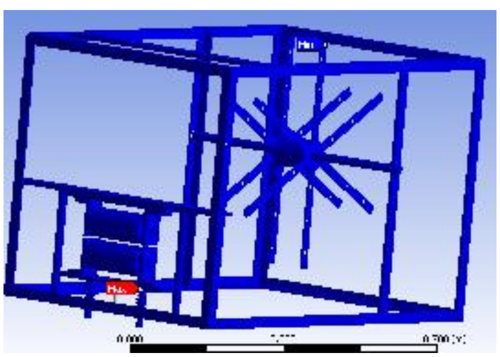

Figure 3: Vonmises stress contour

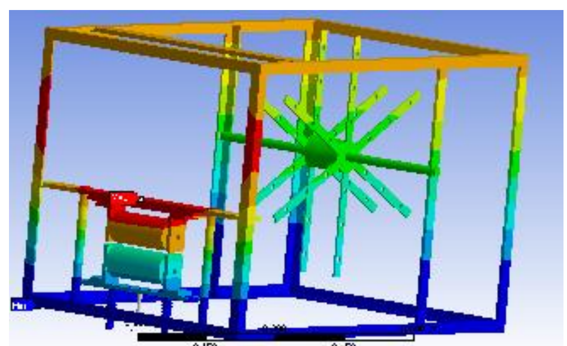

Figure 4: Deformation contour

8. Protection of Steel from Fire

Generally, unprotected steel in a high temperature environment shows poor performance as a structural material, because steel has a high thermal conductivity and the members made of steel usually have thin cross sections. Figure 5 shows the rise in temperature of the protected and unprotected steel exposed to the fire with respect to the rise in temperature of the fire. From the figure 1 it is clear that the time required by unprotected steel to attend the particular temperature is quite less than that of protected steel. Hence time required to reach the temperature of 500°C (temperature up to which the property of the steel remains unchanged) by unprotected steel is approximately 15 minutes while that of protected steel is 35 minutes. Hence the use of fire protected steel for the manufacturing of the trailer gives 20 minutes extra as compared to that of unprotected steel. These 20 extra minutes are extremely crucial during the fire fighting and reduces the further damage due to fire. From figure 1 it is clear that the rate of temperature rise in case of the protected steel is much slower than that of the unprotected steel because the diffusion of surrounding heat into the steel is difficult in protected steel. Following are the ways to protect steel from fire.

8.1 Fire resistant steel

Fire safety in steel structure is brought by the use of certain types of steel, which are called 'Fire Resistant Steel (FRS)'. These steels are basically thermo-mechanically treated (TMT) steels which perform structurally much better than the ordinary structural steels. These steel have ferrite-pearlite microstructures of ordinary structural steels but the presence of molybdenum and chromium stabilizes the microstructure even at 600°. The composition of fire resistant steel is presented in Table 3. The fire resistant steels exhibit a minimum of two thirds of its yield strength at room temperature when subjected to a heating of about 600° C. In view of this, there is an innate protection in the steel for fire hazards. Fire resistant steels are weldable without pre-heating and are commercially available in the market as joints, channel and angles.

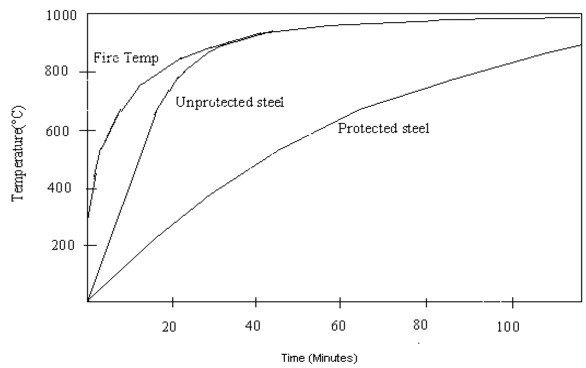

Figure 5: Temperature for protected and unprotected steel exposed to fire

8.2 Fire Proofing

Typical fire proofing materials for steel structures are sprays (mineral fiber, vermiculite plaster), boards (fiber-silicate or fiber-calcium-silicate, gypsum plaster) and compressed fiber boards (mineral wool, fiber silicate). Figure-6 shows two standard fire curves corresponding to combustible cellulose material and a mineral of petrochemical origin. Steel temperature for a structural beam for unprotected and protected steel together with a standard fire temperature is shown in figure 6. Apart from the fire resistant steel, there are some fire protection methods. These methods are basically dependent on the fire load, fire rating and the type of structural members. The commonly used fire protection methods are briefly enumerated below.

8.2.1 Spray Protection. The thickness of spray protection depends on the fire rating and size of the job. This is relatively low cost system and could be applied rapidly. However due to its undulating finish, it is usually preferred in surface, which are hidden from the view.

8.2.2 Board Protection. This is effective but expensive method. Board protection is generally used on columns or exposed beams. In general no preparation is necessary prior to applying the protection intumescing coating. These coating expand and form an insulating layer around the member when fire breaks out. This method does not increase overall dimensions of the member.

8.2.3 Concrete Protection. This method is a traditional fire proofing method but is not employed in structures build presently. The composite action of steel and concrete can provide higher load resistance in addition to high fire resistance. However this method results in increases dead weight loading compared to a protected steel frame. Moreover, carbonation of concrete aids in encouraging corrosion of steel and the presence of concrete effectively hides the steel in distress until it is too late.

10. Industrial Application

Fire prone industries such as petrochemical, oil & natural gas, steel usually witness frequent fire accidents. In the most of the cases, damages and casualties are more because of the time required in extinguishing the fire with the help of conventional fire fighting system. The proposed trailer can be very efficient in such cases. As the trailer works on hydraulic energy, no additional power is required and it can easily enter the fire zone and attack the fire source. We can avoid human casualties, occurring in case of conventional firefighting to the greater extent.

Table 3: Chemical Composition of FRS

	FRS	M.S.
C	≤ 0.20 %	≤ 0.23 %
Mn	≤ 1.50 %	≤ 1.50 %
Si	≤ 0.50 %	≤ 0.40 %
S	≤ 0.040 %	≤ 0.050 %
P	≤ 0.040 %	≤ 0.050 %
Mo+Cr	≤ 1.00 %	--

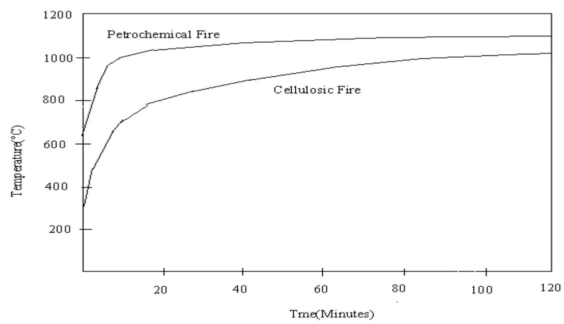

Figure 6: Fire Curves

11. Conclusion

The paper concentrates on determination of the characteristics of the trailer, investigating the compatibility of the trailer material at high temperature operating conditions, observing the response of the trailer under static loading conditions. For linear static thermal analysis, the stress distribution and deformation profile of the trailer, subjected to various loading conditions had been determined. Obtaining the temperature at which the properties of the steel changes. The actual operating condition in which the water monitor trailer is going to be work has been obtained. At the same time, the time required by the trailer to reach up to particular temperature is also obtained. Safe working time, the trailer can spend inside the fire without thermal damage to the trailer is also obtained. Variation in the mechanical properties of the steel under fire is obtained. Also the methods of fire protection for the steels are discussed. Fire protection increases the time that the trailer can spend in the fire zone for extinguishing the fire considerably. This helps in reducing the damage that fire may cause and helps the society in a greater deal.

Reference

[1] Research Proposal on Design and development of hydraulically driven fire fighting trailer by Prof. Prashant S. Kadu.
[2] T. H., Fui, and R. A., Rahman, 2007, "Static and Dynamic Structural analysis of Truck Chasis", Journal Mekanikal, Malaysia, 24, 56-67.
[3] Patent application Hei-6-79011, Japan.
[4] Ramamurtham, S., and Narayan, R., 1992, 1Strength of Material , Dhanpat Rai & Sons, Delhi, 81-183.
[5] Browell, R., and Hancq, A., 2006, "Calculating and Displaying Fatigue Results", March 29.
[6] Hancq, D. A., 2003, "Fatigue Analysis in the Ansys Workbench Environment", Ansys Inc.
[7] Wickström, U., Duthinh, D., and McGrattan, K., 2007, "Adiabatic Surface Temperature for Calculating Heat Transfer to Fire Exposed Structures", 11th Int. Interflam Conference, Sep. 3-5.
[8] Gbado, A., 2002, "Development and Testing of Sugarcane Juice Extractor", National Cereals Research Institute, Badeggi PMB 8, Bida, Nigeria, 4, 103-107.
[9] Mannering, F.L., Kilareski, W.P., and Washburn, S.S., 2005, Principles of Highway Engineering and Traffic Analysis, Third Edition).
[10] Palm Beach County Fire Rescue, Driver Operator Manual, Chapter 3, Fireground Hydraulics, Revised 12/2004.
[11] S. R. Satish Kumar and A. R. Santha Kumar, Indian Institute of Technology Madras, Design of Steel Structures.