Life safety in single story steel frame buildings, Part I - deterministic design
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1 Abstract
This paper discusses fire safety design of single story-, single compartment buildings and evaluates whether time to structural damage is a relevant criterion when lethal fire conditions develop long before any structural fire damage can occur. Current performance-based design practice aims at achieving the life safety objective by preventing structural failure for the entire duration of a natural fire or for a fixed time of standard fire exposure. Prevention of structural fire damage is always relevant for multistory buildings, or buildings with complex geometries as structural fire damage may then threaten occupants and/or firefighters outside the area directly affected by the fire. However, for single-story-, single-compartment buildings, prevention of structural fire damage is less relevant in relation to the life safety objective.

The advantage of the new design philosophy presented in this paper is the possibility to define how the level of structural fire resistance in single-story-, single-compartment buildings can be determined in a consistent way. This level of fire resistance requirement in these buildings differ amongst countries but could be harmonized by accepting of the design philosophy suggested in this paper.

The proposed approach is demonstrated in a design case study of a steel truss in a typical Swedish single-story steel frame building. While not complying with deemed to satisfy fire resistance ratings, it is argued that the proposed design still can fulfill the life safety objective.

Keywords: Structural fire safety design, Performance based design, fire engineering, life safety

2 Introduction
2.1 Background
National building authorities require different levels of structural fire protection to achieve the life safety objective in buildings (Strömgren et al., 2014). The most common way to address the life safety objective is to associate life safety to a fire resistance time requirement, e.g. R 30/60, or, as in performance-based design as no failure during an entire fire.

Sandström et al (2017) introduced the concept of dividing the requirements into no failure during an entire fire and no failure during a limited duration of a fire as a tool for understanding the fire resistance requirements. As the requirement no failure during an entire fire is clear and well defined, it is not elaborated on further in this paper. However, the connection between times of fire resistance and the life safety objective for the requirement no failure during a limited duration of a fire is not clear creating a situation where structural fire resistance requirements are based on magical numbers (Law and Beever, 1995).

This paper presents a structural fire safety design study of a single-story steel frame building adopting the approach by Sandström et al. (2017). The approach is based on the principle that structural fire damage shall be prevented in locations where survival from thermal exposure is possible. As firefighters are better protected against harmful environments, the focus in this paper is on preventing structural fire damage in relation to the capabilities of firefighters. Thus, when the assessment at a structure fire permits firefighting in a given area, the probability of structural fire damage should be prevented. On the other hand, if the fire conditions due to high thermal exposures in a given area make firefighting impossible, then additional structural fire protection does not decrease the risk of injury or harm to firefighters.
Using thermal exposure for estimation of lethality simplifies the comparison to structural fire damage as both the lethality and structural fire damage then stems from high fire temperatures. The approach and design methodology are elaborated on in more detail in the following sections.

2.2 Limitations

The limitations in the study are that:

1. Societal-, economic- and environmental values are not considered,
2. The structural response model only accounts for failure according to element analysis of the truss members, not accounting for any global behavior,
3. Active fire protection measures such as sprinklers and smoke ventilation are not considered,
4. Toxicity is not considered as firefighters are protected against toxicity to a much larger extent than against thermal burns,
5. The conditions for lethality due to burn injuries are determined based on calculations and information found in the literature, see section 2.4.

2.3 The life safety objective

The approach to structural fire safety design used in this paper considers life safety as the sole design objective as presented by Sandström et al. (2017). Sandström et al. states that the structural fire damage affecting an area, \( A_{str} \), at the time of structural fire damage, \( t_{str} \), can be accepted if lethal fire conditions have already developed in the same area.

A critical level of thermal radiation, \( q_{rad,crit}'' \), does not imply immediate lethality to firefighters but by prolonging the exposure over a time, \( t_{margin} \), survival is precluded even if a firefighter enters the building at \( t(q_{rad,crit}) \) without prior heating. \( t(q_{rad,crit}) \) is referred to as \( t_{crit} \) in the remainder of this paper. Even though pre-heating of the human body is relevant when analyzing firefighter safety (Lawson, 1996), it is ignored in this paper. Thus, lethal conditions is present in an area when the thermal radiation is higher than \( q_{rad,crit}'' \) and has been so for at least \( t_{margin} \), see Figure 1.

![Figure 1 Relation between \( t_{crit} \), \( t_{margin} \) and \( t_{str} \). The time range when structural collapse yields acceptable consequences is indicated.](image-url)
This is formulated as the failure criterion for the area $A_{str}$

$$t_{str} < t_{crit} + t_{margin}$$  \hspace{1cm} (1)

2.4 Lethal fire conditions

Lethal fire conditions are defined as a condition where it is impossible to survive even for very short times (Sandström et al., 2017). The lethal conditions as applied in this paper is determined as a combination of thermal radiation, $\dot{q}'_{rad,crit}$, and time, $t_{margin}$, as shown in Figure 1. $\dot{q}'_{rad,crit}$ is estimated based on a literature review. $t_{margin}$ is determined from complementing calculations as shown below.

To estimate the time to burn injuries from surface heat flux, thermal burn is calculated using Henriques burn integral, HBI (Barker et al., 2006). The time to lethality is then defined as the time to reach third degree burns over the entire body, or HBI > 1.0. This agrees with suggestions by Hymes et al. (1993). For this paper, thermal exposure is assumed to act simultaneously on the entire body.

The time to HBI > 1.0 for different values of $\dot{q}'_{rad,crit}$ is calculated using the one-dimensional numerical approach (finite element) for skin temperatures as presented by Torvi and Dale (1994). Calculated values are shown in Table 1 where clothing and skin properties are as suggested by Jiang et al. (2010).

Torvi et al. suggests a two-step evaluation of the lethality from thermal burns for personnel with personal protection equipment, PPE (Torvi et al., 2000). The first step is to determine the time to ignition or deterioration of the PPE, and the second step is to determine the subsequent time to reach HBI > 1.0, see Table 1. The deterioration temperature of the PPE is assumed to be 520 °C which corresponds to Nomex™ in three layers (Kuchta et al., 1969).

As a complement, the time to HBI > 1.0 is also estimated without assumed deterioration of PPE. Calculated times are shown in Table 1.

Table 1 Time to Henriques burn integral HBI > 1.0 for calculations with or without clothing deterioration.

<table>
<thead>
<tr>
<th>$\dot{q}'_{rad,crit}$</th>
<th>Time to HBI &gt; 1.0 for</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{q}'_{rad,crit}$ = 20 kW/m²</td>
<td>54 s (12 + 42)</td>
</tr>
<tr>
<td>$\dot{q}'_{rad,crit}$ = 30 kW/m²</td>
<td>21 s (11 + 10)</td>
</tr>
<tr>
<td>$\dot{q}'_{rad,crit}$ = 40 kW/m²</td>
<td></td>
</tr>
</tbody>
</table>

Two-step method (deterioration of PPE + time to burn) (no deterioration occurs)

<table>
<thead>
<tr>
<th>Two-step method (deterioration of PPE + time to burn)</th>
<th>Two-step method (deterioration of PPE + time to burn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(no deterioration occurs)</td>
<td>123 s</td>
</tr>
<tr>
<td>54 s (12 + 42)</td>
<td>100 s</td>
</tr>
<tr>
<td>21 s (11 + 10)</td>
<td>87 s</td>
</tr>
</tbody>
</table>

$t_{margin}$ should at least be equal to the corresponding higher value for $\dot{q}'_{rad,crit}$ in table 1. For the calculations in this paper, $\dot{q}'_{rad,crit} = 30 \text{ kW/m}^2$ is chosen to occur in the upper range of flashover which usually happens when the incident thermal radiation is in the range of 15 – 30 kW/m² (Peacock et al., 1999). To warrant a design on the safe side $t_{margin} = 150$ s is therefore chosen for this paper.

2.5 Fire-fighting tactics

Standard tactics used in firefighting starts with an assessment of the situation by the commander in chief to evaluate risk versus benefit for entering the fire compartment. If the assessment concludes that no occupants can be alive at the time of arrival, the incentives for firefighters to enter a building with life-threatening conditions are non-existing (Mattsson and Eriksson, 2010). One such strong indicator of a
life-threatening condition is flashover; thus, it is here assumed that fire-fighters do not enter a building after flashover and retreat at first indication of flashover if inside the building. However, if saving lives is considered possible, entering a building can be deemed a viable option regardless of conditions.

Figure 2 shows the possible outcomes of different firefighting decisions at a structure fire. For this paper, there are four outcomes where structural fire failure is relevant to compare to lethal fire conditions. These outcomes are referred to as 1 - 3 in their flowchart boxes respectively.

**Outcome 1** does not present unacceptable consequences regardless of structural fire failure or not.

**Outcome 2** does not present unacceptable consequences if structural fire failure occurs after the time to lethal conditions.

**Outcome 3** does not present unacceptable consequences if structural fire failure due to local fire is prevented.

**Outcome 4** does present unacceptable consequences. However, by preventing structural fire damage for outcomes 1 – 3, the unacceptable consequences are not due to structural fire failure but due to the lethality of the fire conditions in the compartment.

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**3 Case study**

A single-story steel frame building with the dimensions 42 m by 87 m for selling utensils is analyzed. The maximum and minimum building heights are 8.5 m and 6.0 m, respectively. The structural design is based on columns and trusses with a stabilizing steel sheet roof. The lower chord is at a height of 4.6 m at its lowest point, see Figure 3.
The main entrance consists of sliding doors of 3 m by 3 m with an adjacent glass sections of an additional 3 m by 3 m. The entrance is open from the beginning and the glass section breaks after 855 s due to thermal tensions according to the B-Risk glass breakage model as described by Parry et al. (2003).

There is an opening of dimensions 3 m by 3 m for loading goods and six doors of dimensions 1.2 m by 2 m for egress, all assumed fully open.

### 3.1 Steel truss

The element numbers of the truss are presented in Figure 4 and their properties in Table 1.

![Figure 4 Truss layout with element numbers.](image)

<table>
<thead>
<tr>
<th>Steel Quality</th>
<th>Dimensions</th>
<th>$\mu_{0,t_{\text{max}}}$</th>
<th>$A_m/V$</th>
<th>$k_{zh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper chord</td>
<td>S420J L 100x10</td>
<td>0.34</td>
<td>$203 \text{ m}^{-1}$</td>
<td>0.63</td>
</tr>
<tr>
<td>Lower chord</td>
<td>S355J L 100x10</td>
<td>0.23</td>
<td>$203 \text{ m}^{-1}$</td>
<td>0.87</td>
</tr>
<tr>
<td>Diagonals</td>
<td>S355J UNP 100</td>
<td>0.31</td>
<td>$320 \text{ m}^{-1}$</td>
<td>0.78</td>
</tr>
</tbody>
</table>

*Further reference on calculation of shadow effects are presented in section 3.4*

The fire resistance for the steel truss in prescriptive design is determined to 13 min if exposed to standard fire.

### 3.2 Calculation procedure

The calculation procedure using B-Risk (Wade et al., 2016) and the connection to Eurocode calculations is briefly described in Figure 5. Blue boxes represent design input values while black boxes represent deterministic calculations based on these values. If the condition in the last box, $t_{\text{str}} < t_{\text{crit}} + t_{\text{margin}}$, is true, then the failure of the structural element can lead to unacceptable consequences, i.e. firefighter fatality due to structural fire damage.
3.3 Design fire calculations

The fire compartment conditions are calculated using B-Risk, a two zone model developed by BRANZ in New Zealand (Wade et al., 2016). B-Risk is equipped with the ability to perform Monte Carlo simulations making it suitable primarily for the calculations in part II (Sandström, 2019) of this paper. The design values for the fire calculations are presented in Table 2.

![Diagram](image)

Figure 5 Flow chart describing the calculation process. Blue boxes represent design values, while black boxes are calculations using deterministic methods.

Table 2 Fire design values used in B-Risk.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat release per unit area</td>
<td>500</td>
<td>kW/m²</td>
<td>A, B</td>
</tr>
<tr>
<td>Fuel load density</td>
<td>600</td>
<td>MJ/m²</td>
<td>B</td>
</tr>
<tr>
<td>Fire growth rate, α</td>
<td>0.047</td>
<td>kW/s²</td>
<td>B</td>
</tr>
<tr>
<td>Height of fire above floor</td>
<td>1.3</td>
<td>m</td>
<td>Est.</td>
</tr>
<tr>
<td>Horizontal distance from plume centerline to each element in truss</td>
<td>0</td>
<td>m</td>
<td>–</td>
</tr>
<tr>
<td>Thermal inertia of sandwich walls $\sqrt{k\rho c}$</td>
<td>2400</td>
<td>J/m²Ks¹/²</td>
<td>C</td>
</tr>
</tbody>
</table>

A (PD 7974-1, 2003)
B (Guide for Smoke and Heat Venting, NFPA 204M, 1985)
C Approximated for reference according to the method used in (EN 1991-1-2, 2002) annex A.
In the pre-flashover stage of the fire, HRR is calculated according to $\alpha t^2$, while HRR in post-flashover stage is calculated by B-Risk from the available oxygen from openings in the façade, see Figure 6. Only the initial part of the fire development is included to illustrate the fast fire growth, and the fully developed phase of the fire. Flashover occurs in the model after 1 460 s and all fuel is consumed at 28 900 s.

![HRR vs Time](image)

Figure 6 HRR in the fire compartment from calculations in B-Risk.

Thermal action on the steel truss elements is calculated from the gas temperature, $T_g$, assumed as the current maximum value of the hot gas layer, and the plume center line temperature at the corresponding height as suggested by Franssen et al (2001). In this paper, the localized fire temperature in the plume was calculated using the Heskestad approach as adopted in the Eurocodes (EN 1991-1-2, 2002).

### 3.4 Steel temperature calculations

The steel temperature in each element was calculated according to Eurocode 1993-1-2 as shown in the recursion formula:

$$T_{s,i+1} = T_{s,i} + k_{sh} \frac{A_m/V}{c_s \rho_s} \cdot \dot{q}_{tot}'' \cdot \Delta t$$

where $T_{s,i}^i$ is the steel temperature at time step $i$, $k_{sh}$ the correction factor for the section factor, $A_m/V$, to account for shadow effects. $c_s$ is the specific heat of the steel, $\rho_s$ is the density, and $\Delta t$ is the size of the time step. $\dot{q}_{tot}''$ is calculated according to equation (3).

$$\dot{q}_{tot}'' = \varepsilon \sigma (T_g^4 - T_{s}^4) + h_c (T_g - T_s)$$

where $\varepsilon = 0.7$ for steel and $h_c = 35$ W/m²K for natural fires. All material properties used are the temperature dependent steel properties presented in EN 1993-1-2.

For open cross sections, not all surfaces are exposed to an equal amount of radiation. To account for this shadow effect, the perimeter of the cross section is reduced using a correction factor, $k_{sh}$. $k_{sh}$ for the upper and lower chord is calculated to account only for the real amount of radiation heating the cross section (EN 1993-1-2, 2005; Franssen and Vila Real, 2010; Wickström, 2016).
For both the upper and lower chord, the combined cross section perimeter of the angled elements is considered as shown in Figure 7.

![Figure 7 Assumptions of the combined cross section perimeter for calculation of the section factor including shadow effects for the lower (left) and upper (right) chord.](image)

For the upper chord (to the right in Figure 7), the upper faces of the elements are partly shielded by the corrugated steel sheet as illustrated in Figure 8.

![Figure 8. The upper face of the upper chord is partially exposed due to the corrugated steel sheet.](image)

Table 1 shows the section factors and shadow effect correction factor, $k_{sh}$, for the different upper and lower chord, and the diagonals.

### 3.5 Load calculations

The characteristic snow load for the city of Skövde in Sweden is $s_k = 2.5$ kN/m², the shape factor for the roof, $\mu_i = 0.8$, and the partial coefficient for accidental loads in Sweden is the frequent value factor, $\psi_1 = 0.4$ (Boverket, 2016). The evenly distributed accidental design load was calculated as

$$E_{d,fi} = G_k + \psi_1 \mu_i s_k = 0.77 + 0.4 \cdot 0.8 \cdot 2.5 = 1.57 \text{ kN/m}^2$$

Data on the characteristic dead load, $G_k = 0.77$ kN/m², was presented by steel truss manufacturer.

### 4 Results

#### 4.1 Time to lethal conditions

At the time of structural fire failure, $t_{str}$, flashover has occurred, and the compartment can be considered well mixed with uniform temperature in the entire compartment. Thus, thermal radiation to occupants is estimated only from the hot gas layer temperature, $T_g$, ignoring the direct thermal radiation from the plume. The time to lethal fire conditions, $t_{crit} + t_{margin}$, is calculated to 3140 + 150 s after ignition, e.g. $t_{crit}$ is an output from the fire model as the time when the thermal radiation from the hot gas layer reaches 30 kW/m² and $t_{margin}$ is decided according to section 2.4, see Figure 9. Figure 9 also shows the
steel temperature and time to structural fire failure, $t_{str}$, for the most critical element in the steel truss, element 3 (green cross).

![Figure 9 Global hot gas layer temperature and local steel temperature for the most critical truss element, element 3.](image)

Initially, the steel is heated by the localized fire, thus the steel element temperature, $T_s$, is higher than the global hot gas layer temperature, $T_g$.

### 4.2 Cost estimation

Deemed to satisfy solutions, or code compliance for steel trusses in national building codes are usually based on classification equivalent to R 30 or R 60 (Strömgren et al., 2014), and the most common way to achieve this for steel trusses is to apply fire intumescent paint. The cost is estimated by asking an entrepreneur for the cost of applying fire intumescent paint equivalent to R 30 (175 SEK/m²) and R 60 (275 SEK/m²) in comparison to regular corrosion protection paint (50 SEK/m²). The cost for the steel is based on the list price given by the steel truss manufacturer. Figure 10 shows the relative cost for the different deemed to satisfy solutions compared to the studied design case in this paper.
5 Discussion

By shifting focus from time as a sole criterion to a more holistic view of the design, it is shown that life safety can be achieved even though the deemed to satisfy solution, i.e. R30/60, and no failure during an entire fire objective are disregarded. This change in perspective on structural fire resistance requirements shows a feasible path forward for achieving the life safety objective in a more nuanced way than previously possible.

Even though the approach creates room for a more nuanced design and, in this case unprotected structural elements, classification will always be needed for rational design solutions. The approach in this paper should rather be considered a complement to classification, and a way to interpret building code objectives.

In the studied fire case, the lower chord was designed to withstand the direct thermal impact from the localized plume fire prolonging the time for structural fire failure until after flashover and past the time to lethal fire conditions. Thus, instead of fulfilling the deemed to satisfy solution presented as time of fire resistance, the design strategy in this paper can be condensed to:

1. Prevention of structural damage due to localized plume fire, and
2. Prevention of structural fire damage prior to the time to lethal fire conditions due to incident thermal radiation from the hot gas layer.

Fire fighter safety is difficult to estimate as personal protective equipment, PPE, enables firefighters to work in very hot environments without sensing the heat. This is beneficial as the PPE prevents injury if the firefighters retreat in time, but the protection given by the PPE can also prevent firefighters from correct interpretation of the thermal danger.

There is much in this field to explore and thoroughly evaluate in order to find practical adaptations for different structural configurations as well as a reasonable balance between structural integrity and life safety both with regards to design numbers as well as firefighting tactics. However, it is the authors strong conviction that finding these common principles are possible and that this paper presents a way for doing that.
6 Conclusion
This paper has shown that the steel trusses in the studied building can be safe without additional fire protection. This reduces building cost without increasing the probability of unacceptable conditions due to structural damage.

It has also been shown that the life safety objective can be achieved even for structures that does not comply to deemed to satisfy fire resistance time requirements. Thus, fire resistance time itself should not be regarded as the sole criterion to meet in structural fire safety design, rather one among others such as no failure during an entire fire or structural stability in fire until after the time to lethal fire conditions.

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8 References

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