DESIGN AGAINST PROGRESSIVE COLLAPSE OF BUILDINGS IN FIRE

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Progressive Collapse

The objective of this article is to focus attention on the physical performance of buildings in fire and the relationship between design philosophy and structural response.

Traditionally structural fire safety design has been limited to elemental performance considerations. Examples of this are the designation of walls or floors as having a specific fire resistance irrespective of how they are integrated into the whole structure. In their current form the Proposed Building Regulations in Ireland are primarily concerned with life safety and do not require the whole building 'reaction-to-fire' phase to be considered. However, having provided for regulatory requirements in relation to the safety of building occupants greater benefit in respect of the minimisation of property loss can be achieved for little extra cost. Indeed frequently it might be a question merely of using materials more wisely to this end rather than incurring further expenditure. Conventional structural fire safety design pays little attention to the protection of property or the safety of fire fighters or occupants who cannot exit quickly in an established fire situation.

The term 'progressive collapse', which dates back to the Ronan Point collapse of 1968, is employed to describe the collapse of structural elements remote from the scene of an isolated overloading incident. The Ronan Point Inquiry (Ref. 1) found that the collapse exposed a weakness in system building which had not been considered in the original design. The building was considered safe for all normal uses, but account had not been taken in the design of the consequences of an abnormal incident which could, for instance, cause failure of one or more load-bearing members.

Design Objectives

Over the last twenty years designers have taken on board the lessons of Ronan Point in respect of static and dynamic overload considerations.

UK Building Regulations were amended to require buildings of five stories and over to be designed so that any one (at a time) element of the structure which is essential to its stability must be designed to withstand, just short of failure, a pressure of 34 kN/m^2. Alternatively, if the element of structure cannot be designed for this purpose then it must be assumed to have been removed and the rest of the structure must not collapse outside prescribed limits.

The Proposed Building Regulations in Ireland, dealing with buildings of five or more storeys, require that if any one structural member (a member essential to the structural stability of the building) were to be removed:-

(A) structural failure consequent on the removal would not occur within any storey other than the storey of which it forms part, the storey next above (if any) and the storey next below (if any); and

(B) any structural failure would be localised within each such storey.

Where an external corner is formed by two loadbearing walls simultaneous removal of portion of both walls must be considered. Portion of a structural member that is capable of sustaining a load of $34kN/m^2$ together with associated and normal loads need not be removed for the purpose of the analysis described above. These constraints are similar to those included in the Building Regulations of England and Wales.

Current structural design codes and standards in Ireland and the U.K. include provisions for limiting the spread of building failure in the event of accidental overload to the localilty of the accident. I.S. 325 Code of Practice for Use of Masonry, Part 1: Structural Use of Unreinforced Masonry (Ref. 2) emphasises that "a designer responsible for the overall stability of the structure should ensure compatability of the design and details of parts and components". There should be no doubt of this responsibility when some or all of the details are not made by the same designer. This point was also taken up by the Engineering Institutions in their report to the Government Task Force on multi-storey buildings (Ref. 3).

Similar constraints can be readily introduced in respect of fire safety design. For the maximisation of safety and minimisation of loss of property it is necessary to consider the fire response of the whole building in the design. The objectives of the design approach should be to:

(a) ensure the building design meets the lower bound of safety in early stages of fire such as building regulations provide for;

(b) ensure the safety of fire fighters through the more predictable behaviour of structure at both early and later stages of fire;

(c) minimise the extent of fire damage through designing for predictable behaviour in fire including zone isolation principles and control joints;

(d) facilitate reinstatement through improved awareness of the behaviour of materials in fire, clean breaks of structure and fabric, thermal shielding of metal, judicious placing of concenrated loads and control joints.

Design Principles

The principles applying to the provision of safety in the early stages of fire rarely involve a design process. With the number of prescribed solutions offered by industry on a component basis the issue of one element rendering ineffective the performance of an adjacent element is not adequately pursued.

(i) Thermal Expansion:

ISO 834-1975 (E) "Fire resistance tests - Elements of building construction" and also B.S. 476 : Part 8 : 1972 "Test Methods and Criteria for fire resistance of Elements of Building Construction" give the time-temperature relationship for test furnaces (Fig. 1). The expansion of typical construction elements for various intervals of exposure to fire are given in Table 1. The significance of time-temperature relationships even for relatively short intervals of exposure to fire can be judged from this. Steel and aluminium will have undergone radical changes in respect of mechanical characteristics at relatively low temperatures.

Steel roof purlins extending to two or more bays in an industrial building and passing over a compartment wall present a high risk of horizontal fire spread through roof disruption. This may arise from direct linear expansion of purlins or through tearing of roof fabric, AA, AB or AC rated, local to a compartment wall but over the compartment next to the fire compartment. A similar problem arises where purlins from adjacent bays are tightly butted over a compartment wall. Horizontal fire spread will take place either through direct linear expansion or by bow-type buckling of purlins in compression (Figs. 2(a) and 2(b)).

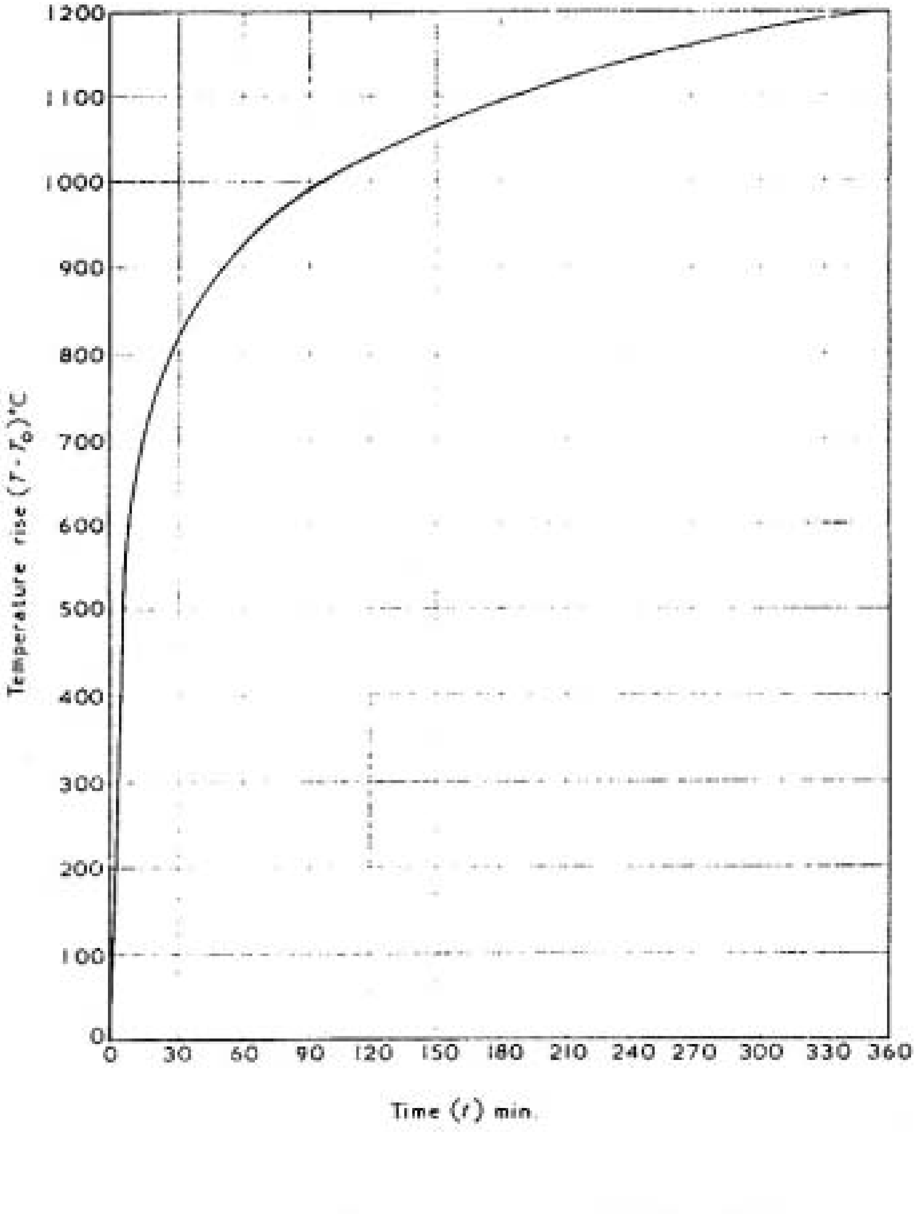


Fig. 1. Standard time-temperature curve.

TABLE 1 : TIME-TEMPERATURE RELATIONSHIPS FOR TYPICAL CONSTRUCTION ELEMENTS

Time in Mins.	Temperature Rise in Furnace $(T-T_o)$	* Expansion of Steel Beam 10 m in Length	* Expansion of Aluminium Beam 10 m in Length	* Expansion of Reinforced Concrete Beam 10 m in Length	
5	556	67	133	45 - 89	
10	659	79		45 - 92	** Variation with concrete quali and aggregate type.
15	718	86		50 - 100	
30	821	98		50 - 115	
60	925	111		60 - 130	
90	986			60 - 138	

*Expansions are given in mm.

Notes:
(i) Aluminium softens at 400°C thereby ceasing to act structurally.
(ii) The temperature at which the flow stress of mild steel falls to the design stress is generally taken to be about 550°C - for a design factor of safety of about 2.
(iii) Loss of prestress in prestressed concrete can occur at early stages of fire particularly if spalling occurs.

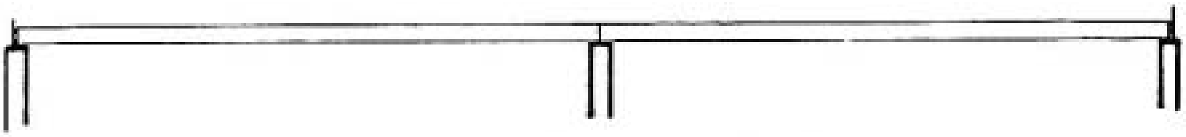


Figure 2(a) Two bay purlin arrangement.

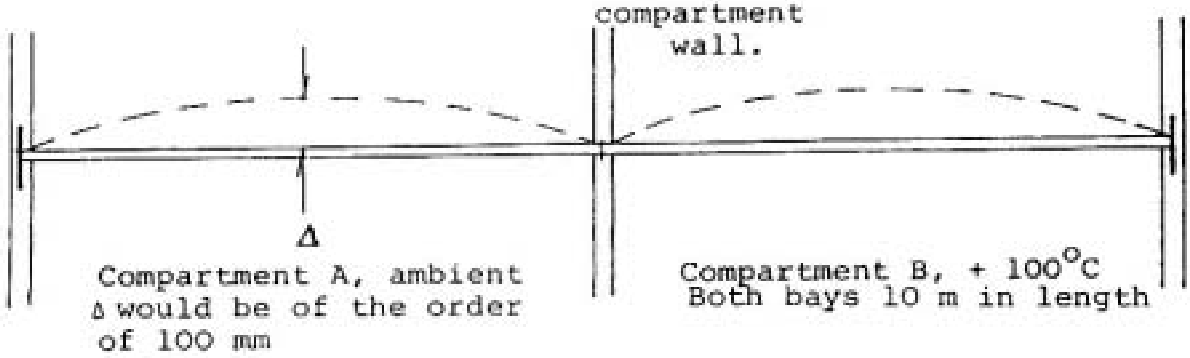


Fig. 2(b) Extent of pressed steel purlin bowing over compartment A due to fire in compartment B.

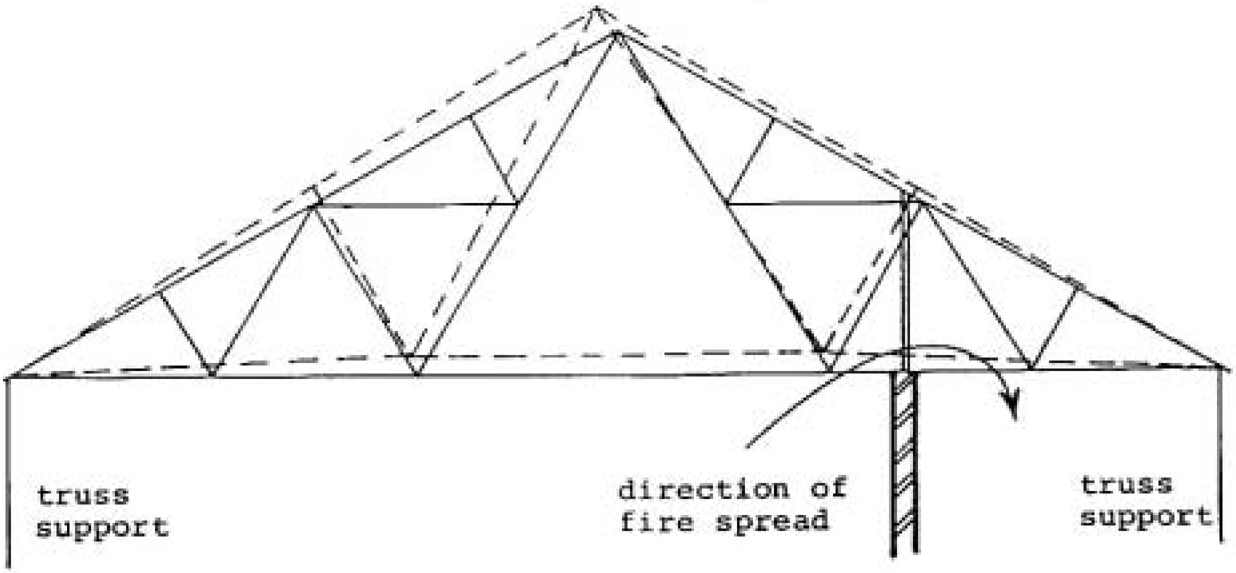


Fig. 2(c) Opening of fire seal over compartment wall resulting from truss supported independently of compartment wall.

The response of a steel roof truss when continuous over two bays and with fixed end supports is likely to lead to horizontal fire spread by opening the seals at fire stopped junctions (Fig. 2(c)).

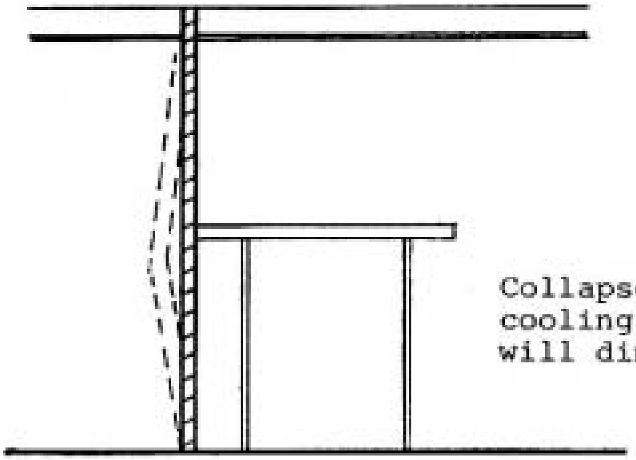
Light steel structural elements also require to be fire protected if reinstatement is to be minimised. Steel lintels without fire cover are likely to induce buckling of masonry walls necessitating complete demolition in certain circumstances. Similarly the reinstatement of floors bearing on joist hangers will prove difficult because of the distortion of the hangers. It is likely that reinstatement will require complete reconstruction of masonry walls in this situation.

Conventional fire safety design fails to predict structural behaviour on a time variable basis. This is particularly so in relation to horizontal fire spread. The concept of vertical separation should be the major consideration at building design stage. Linked with this should be a Fire Defence Plan and the entire design should be based on the assumption that a fire will break out in any particular location either by accident or intention. The boundary to fire spread must be determined by the designer. The response of the construction should be predictable almost on a minute-by-minute basis.

(ii) <u>Integrity of Compartment and Separating/Party Walls:</u>

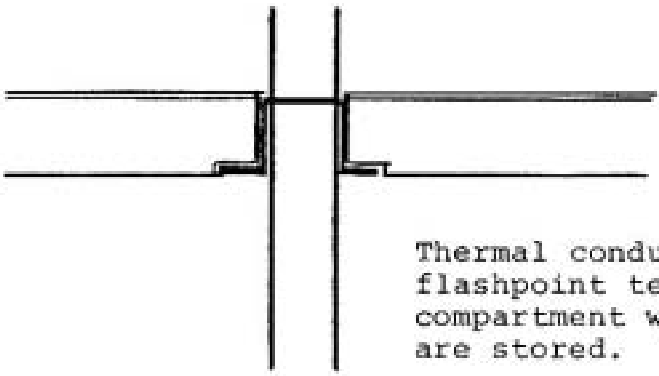
Compartmentation entails the division of a building into fire-tight compartments by fire-resisting elements of building construction in order to contain a fire within the compartment of origin <u>and</u> to prevent smoke and other damage to adjoining compartments. Over and above the by-passing of compartment walls already discussed it is essential that the walls themselves fully retain their integrity during all stages of a fire and for a period afterwards when there may be danger from collapse of adjacent structures. For instance, if heavy steel sections pass through a wall the movements at low temperatures described earlier will displace masonry surrounds and/or fire seals. Metals structures prone to buckling during a fire will damage large areas of masonry panelling (Fig. 3(a)). Cast iron columns raise particular problems where collapse may result due to thermal shock from fire fighting water.

The designed fire resistance of a compartment wall must be retained in respect of 'integrity', 'insulation' and 'stability'. Structural fixings must be designed to uphold this principle. Movements induced at the early stages of a fire will fracture a compartment wall (Fig. 3(b)) where the structure is fitted tightly against both sides of the wall. Conduction through joist hangers penetrating a wall will create high local temperature conditions on the 'cold' or unexposed side causing fire spread to combustible surfaces and finishes as well as stored materials (Fig. 3(c)).



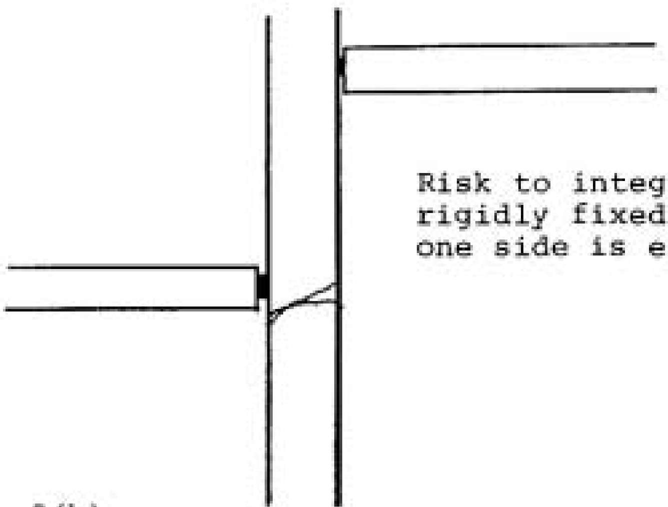
Collapse of Mezzanine Floor due to shock cooling of cast iron columns in fire fighting will diminish integrity of compartment wall.

Fig. 3(a)



Thermal conductivity of metal hanger can lead to flashpoint temperatures on 'cold' side of compartment wall where flamable materials are stored.

Fig. 3(c)



Risk to integrity of compartment wall due to rigidly fixed stepped roof situation when one side is exposed to fire.

Fig. 3(b)

Openings in compartment boundaries (whether vertical or horizontal) should be avoided. Where door openings or service openings have be be provided their number should be kept to an absolute minimum but their design must ensure that the integrity of the boundary is not impaired when fire occurs. Openings, for any reason, in separating or party walls must be avoided.

(iii) Collapse Movements:

In timber framed housing structural interaction has led to unpredicatble fire spread. In the platform construction system (Fig. 4(a)) the sagging of first floor joists leads to opening of the cavity in upperstorey walls in a relatively short time. An engineered design (Fig. 4(b)) will obviate this phenomenon and render the structural behaviour more predictable.

While these behavioural characteristics are based on well known principles they are rarely taken into account at design stage or employed to predict structural behaviour in fire. The inclusion of heavy concentrated point loads such as roof water tanks also presents a high risk of unpredictable behaviour in fire. When, through burning, the load factor of timber roof trusses is reduced below unity there will be a sudden unpredicatble release of load leading to the collapse of the ceiling membrane with consequent high risk to the safety of fire fighters.

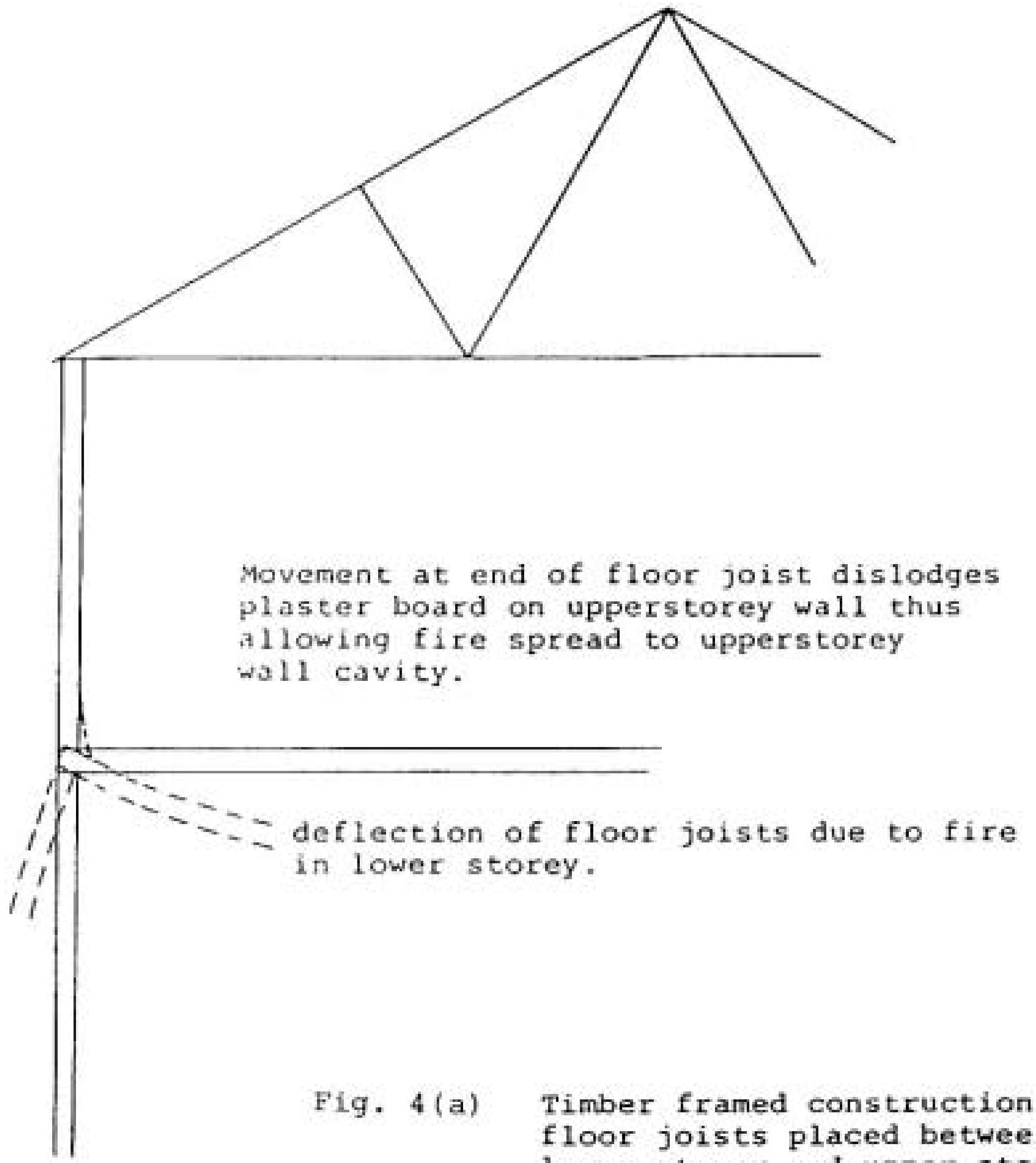


Fig. 4(a) Timber framed construction with floor joists placed between lower storey and upper storey walls.

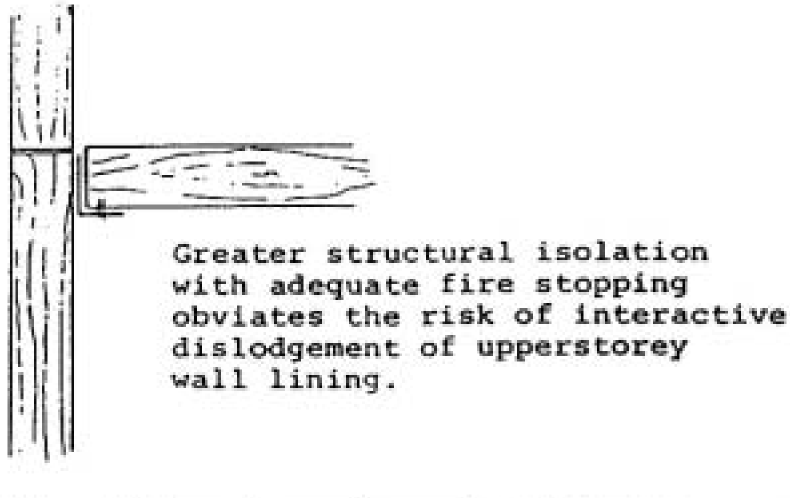


Fig. 4(b) Timber framed construction-An Engineered solution.

(iv) Engineered Collapse:

Through knowledge of the time-temperature variation characteristics of a fire the behaviour pattern for construction components can be predicted. Material responses can be harnessed judiciously to create yield lines at predetermined locations. Also, a good estimate of the period of fire to reach a specific yield line can be made.

A typical situation where this approach would be pertinent is the party wall location in terraced housing. Here the objective would be to develop a clean line break at party wall locations while maintaining the full integrity of the fire stop and the wall.

Tiling battens continuous across the top of a party wall violate this principle. The threat of disruption of fire seals at batten level or at fascias and soffits is unacceptable. Ideally the entire roof construction over the compartment should be designed to collapse onto the fire. The Whyburn Primary school design (Ref. 4) and the Firbar fire stopping system (Refs. 5 and 6) are based on the concept of engineered collapse. In the Whyburn School design the building was divided into compartments by one hour rather than half hour walls in keeping with the principle of not only catering for escape time but also ensuring defence against horizontal fire spread.

The roof and ceiling collapse here were engineered through the use of specially designed support systems developed to bring about ceiling collapse at specific temperatures. Venting the fire to the roof construction was thus predictable and precuations were taken to minimise damage to compartment walls during roof collapse.

In the course of large scale fire testing of the Firbar system collapse of the roof over the fire compartment was in accordance with design while adjoining roofs were preserved perfectly intact. Similar test observations on traditional construction led to opening of routes for fire spread through tilting of battens, fascias and soffits, necessitating major reinstatement work in the adjoining compartment.

The isolation concept established for domestic housing has also been adopted and developed for use with metal roofs for industrial buildings. Predictable behaviour of purlins when subjected to fire has been 'engineered' through the provision of freedom to expand for the purlins together with the development of free rotation at the ends of the purlins over the fire compartment. This is achieved primarily by selecting a bolt tightening system which will relax at specific temperatures thereby allowing the prediction of roof collapse and achieving a clean break over the compartment wall.

Design Application

A school in Limerick has recently been designed (Ref.8) on the basis of applying these principles:

Again the design proposed here was based on the principle of vertical separation and the use of engineering details with predictalbe behaviour. For this project the plan form is shown schematically (Fig. 5(a)). In the design fire breaks were used in conjunction with a structural control system designed to maintain the integrity of a fire stop, provide a clear break at the firestop location (Fig. 5(b)) and maintain the integrity of the roof (AA, AB or AC) at the side away from the fire.

The solution here was to obviate unpredictable structural behaviour by using trusses at each side of the plane of isolation thereby ensuring the integrity of the classroom/corridor compartment wall. Above ceiling a curtain fire barrier was used. Containment of fire damage was thus achieved by providing a fire break or isolation plane along the classroom/corridor wall together with judiciously placed compartment walls of 1 hour rating.

Further Development

Further research on the behaviour of materials and constructions in fire is necessary towards the development of predictable engineered structures.

The gains from more sophisticated design will include:

- Increased safety for fire fighters;
- Increased safety for disabled, and the small percentage of building occupants who will panic in a fire situation;
- Reduction of reinstatement costs.

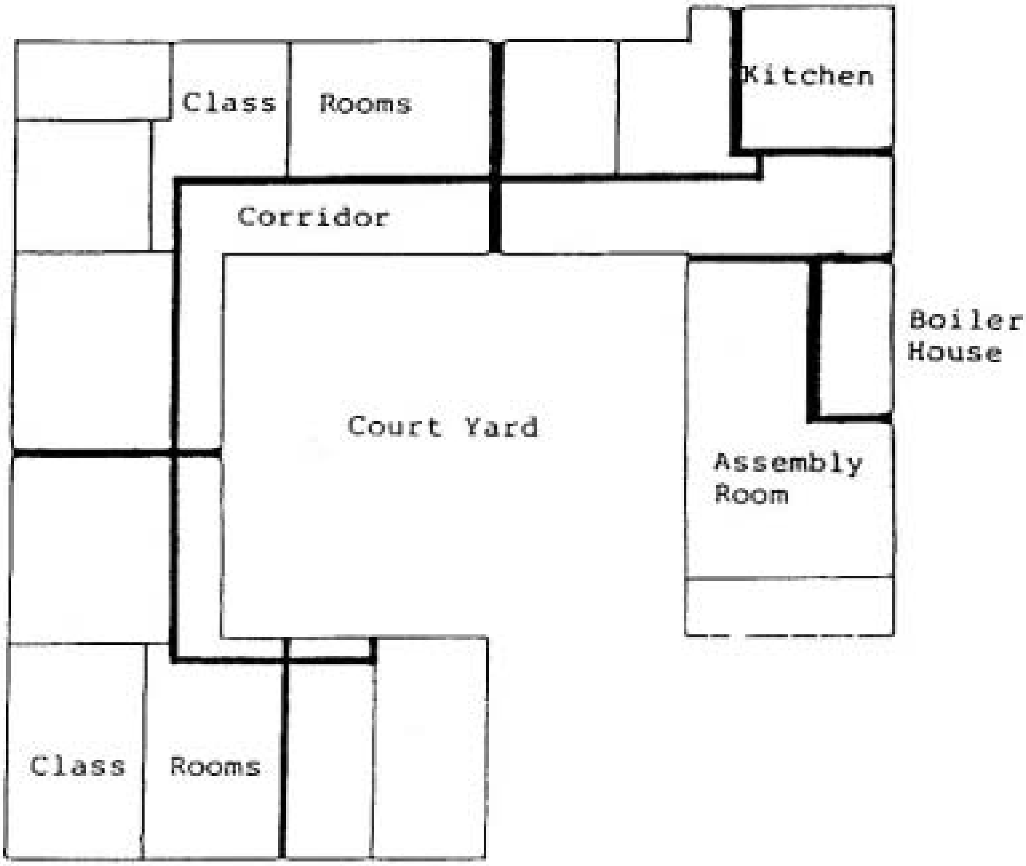


Fig. 5(a) Arrangement of compartment walls for vertical separation.

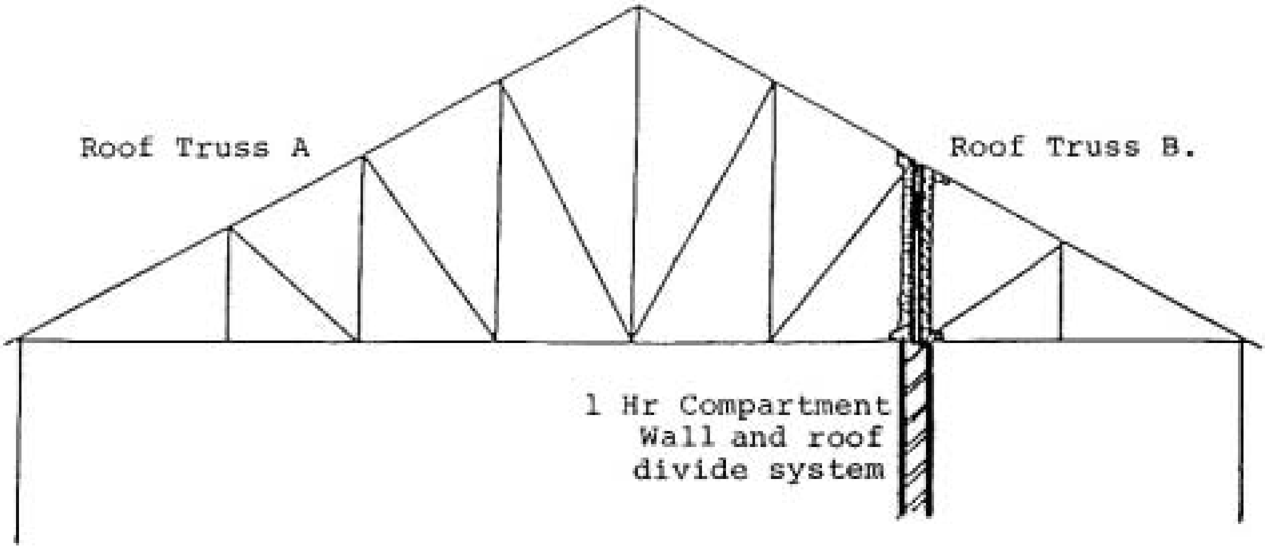


Fig. 5(b) Fire break system at compartment wall location.

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