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PREVENTION OF PROGRESSIVE COLLAPSE IN MULTISTOREY RESIDENTIAL MASONRY BUILDINGS FOLLOWING GAS EXPLOSION

John Springfield[1]

ABSTRACT

Development of the Guideline on resistance to progressive collapse, an Ontario requirement for high rise residential buildings with in-suite natural gas supply, is summarized. Noteworthy is the requirement to consider the failure of more than a single member. Included is a design pressure formula for window vented suites. For the most common types of masonry buildings, precast slab or concrete slab on steel joist floors on concrete masonry cross walls, conceptual design approaches to develop alternate load paths are given. These include both in-plane and out-of-plane arching. Also illustrated are mechanisms for maintaining support of floors.

INTRODUCTION

The proposed introduction of in-suite natural gas service to high rise residential buildings in Ontario caused the Provincial Fuel Safety Branch to question the safety of such a move. The possibility of a Ronan Point type failure was viewed with apprehension. If the accumulation of an air-gas mixture were not prevented by electro-mechanical controls on the gas supply the Branch wished to know the probable consequences.

The Ontario Natural gas utilities firstly commissioned a study of The Effects of Natural Gas Deflagrations on High Rise Residential Buildings in which three commonly used types of construction were addressed, namely:

[1]Structural Engineer, 194 Bayview Heights Drive, Toronto, Ontario, M4G 2Z2.

- reinforced concrete slab and cross wall construction
- reinforced concrete flat slab construction;
- precast slab or concrete slab on steel joist floors supported on masonry cross walls.

These typical North American forms of construction were studied in some detail since they differed in form and in spans from previously studied types in Europe. In Ontario, precast concrete supporting walls were of negligible interest.

A result of this study was the elimination of the two cast-in-place concrete types of construction from concern, recalling that since 1984 it has been mandatory to incorporate structural integrity reinforcement in flat slab construction.

In this initial study, the development and relief of deflagration pressures had been investigated. In view of the extensive research on these topics by the British, their theoretical approach was adopted as the basis for design. This followed the precedent set some years previously by the U.S. National Bureau of Standards and the Portland Cement Association, (NBS & PCA).

The Ontario Gas utilities commissioned the author to develop a Guideline on resistance to progressive collapse of high rise masonry residential buildings which structural designers of new buildings could follow and which, if followed, the Fuel Safety Branch would accept. The remainder of this paper is devoted to an explanation of the Guideline requirements.

PROGRESSIVE COLLAPSE

This phenomenon is defined as follows:

> Progressive collapse is the propagation, by a chain reaction mechanism, of a local structural failure into the failure of a substantial portion of the building, totally disproportionate in magnitude to the initial failure.

A test for resistance was defined as:

> A structure may be deemed resistant to progressive collapse if, by accepted engineering principles, it can be shown that, following a postulated abnormal event, neither the failure of members likely to be affected by the event nor the debris therefrom will induce further sequential structural failure.

Implicit in the above definition of resistance is the requirement to consider two or more elements failing concurrently.

The notion that only single element failure need be considered seems to come from British engineers faced with the unenviable task of strengthening hundreds of existing apartments having little resistance to progressive collapse. They concluded that it was impractical to cope with multiple element failure. (Rasbash).

In defining resistance to progressive collapse, most authorities have adopted the British requirement of resistance to the notional removal of a single member. The author views this as an abstract hypothetical notion, valid perhaps for some abnormal events, but unjustifiable for others. It appears distinctly probable that a gas explosion within an apartment might rupture both floor and ceiling slabs and/or one or more load bearing side walls. The notion that only one element will fail and that by so doing, it will relieve the combustion pressure on the others, is quite fallacious in the author's opinion.

Lacking the luxury of collective committee responsibility, the author found it unconscionable to propose the previously used single element concept in favour of a more realistic approach.

DEFLAGRATION PRESSURE

It is assumed conservatively that the air-gas mixture will be in optimum proportion to produce the highest pressure but that the pressure will be relieved by rupture of the windows. This does not mean negligible pressure rise. Indeed, the dynamics of combustion are such that pressure will continue to rise for some time after glass failure. With 15% window area, pressure is not likely to rise above 15kPa (310psf), but such pressure may still cause severe structural damage. Unlike chemical high explosives, the peak pressure duration of air-gas mixtures exceeds the natural period of vibration typical structural slabs and walls. Consequently, these elements experience the peak pressure as an actual load. Slabs above the deflagration would be adversely affected by reverse bending. Masonry walls not subject to sufficient compressive load from above may rupture under such lateral load.

The Cubbage & Marshall formula is given in an Appendix to the Guideline as a recommended procedure for determining pressures. However, variables such as degree of turbulence and apartment configuration render determination of interior pressures sufficiently approximate to make precise design foolhardy, (Stretch). It is recommended that design of elements that must remain intact be based on the British value of 34kPa (5psi or 720 psf).

RESISTANCE MECHANISMS

To design walls and floors to resist peak pressures from window vented gas deflagrations would render masonry walls and precast slabs or steel joists uneconomic. The prudent approach is to provide alternate paths for wall and floor loads to bypass localized failures.

The particular characteristics of hollow concrete masonry which lend themselves to the provision of alternate paths or enable masonry to resist significant lateral pressures are:

- the ability of common bond masonry to arch in plane over locally damaged zones (Drysdale et al);

- the ability of compressed masonry to arch out-of-plane to resist lateral pressure (Drysdale et al); this simply means that the line of thrust must lie within the cross section, probably more readily recognised as a 3-hinge mechanism; (typically, the 4th storey below a roof can resist vented deflagration;

- the ease with which reinforced bond beams may be formed, providing both flexural capacity and tied arch resistance;

- the relative ease with which vertical cells may be reinforced and grouted to provide both vertical tensile resistance and flexural resistance.

Illustrated examples of mechanisms and details will convey better than discussion the mechanisms developed.

Fig. 1 illustrates one side of a typical building, normally served by a double loaded central corridor. Slab spans would be up to 12m and corridor to exterior non-load bearing wall perhaps 10m. The diagrams follow proposals by Fintel for concrete wall buildings. The author does not favour the diagonal strut supported cantilever for masonry, preferring the arch. Fintel introduced the concept of "strong elements" designed to remain structurally intact during deflagration. Clearly a strong element at each arch support is essential. Return walls form the simplest strong elements, as shown in Fig. 2.

If return walls are not possible, vertically reinforced elements can be formed within a wall, Fig. 3. The author has recommended vertical planes of weakness at the strong elements to predefine separation. By locating them in from the ends, the arch span is lessened, reducing the tie force and facilitating arch formation near the top of the building. Vertical reinforcement is required in the wall to suspend floors from arches above.

The author has used the tied arch concept in repair of Through-the-Wall (TTW) brick buildings suffering from crushing at shelf angles. Arching made it possible for inadequate spandrel beams to support two storey lifts.

The PCA proposed that floor slabs form catenaries to bridge failed walls. The author sees no point in trying to form catenaries of 24m span when slabs may be suspended from walls above. In any event, catenary action in end spans is questionable in view of the required horizontal restraint. The author's mechanism is shown in Fig. 4 at an interior wall and at an exterior wall in Fig. 5. Details of the system for P.C. slabs and steel joists are shown in Figs. 6 & 7.

It is not claimed that providing resistance to interior gas deflagration is easy and without cost penalty. However, in seismic zones 2 and higher, reinforced masonry is required so the premium would be significantly smaller. Regardless, it is the author's opinion that resistance to progressive collapse, based perhaps on the notion of single element failure, be incorporated into all residential buildings.

OBSERVATIONS

Arising from this study and from his hands-on participation in masonry restoration, the author invites comments on his conclusions, and where appropriate, suggests investigation be undertaken:

1. Accept filling of reinforced blockwork cells with mortar, or modified mortar, by the mason as he lays up the blockwork as an alternative to grouting. Compressive strength is not significant. The important factors are bond and elimination of voids.

2. To what extent do vertical joints contribute to the characteristics of masonry, other than for barrier purposes? Frequently vertical joints have not been well filled.

3. In brickwork, English bond and Flemish bond, although widely thought to be excellent, are poor in resisting vertical cracking and bridging locally deficient support. The close proximity of vertical joints (50mm) provides little tensile overlap of one brick on another, permitting almost vertical cracking. Common bond is much to be preferred.

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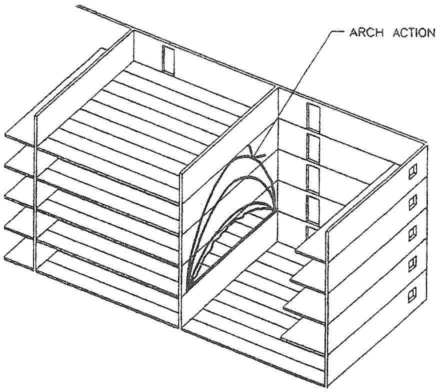
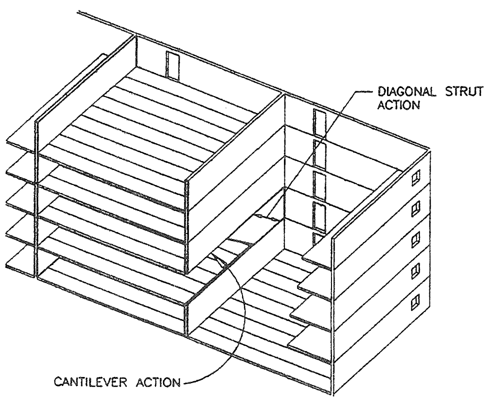


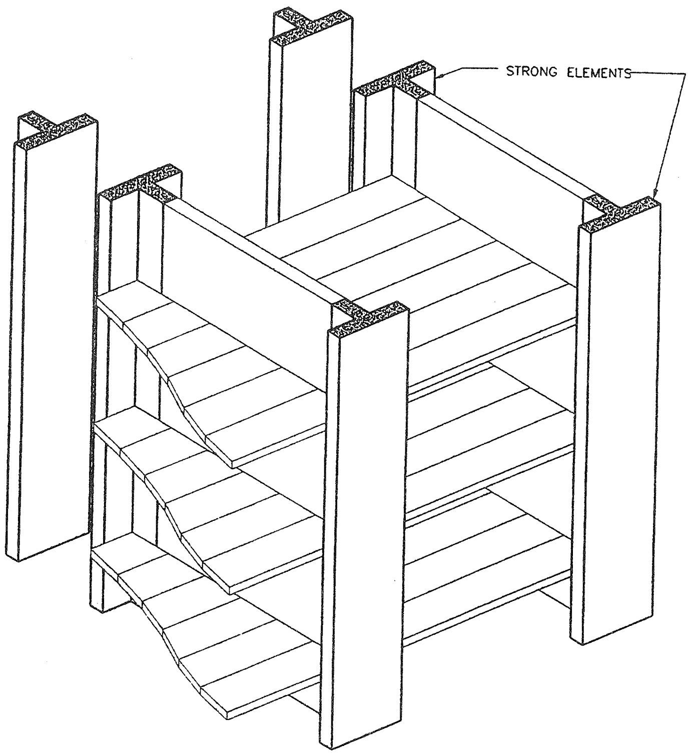
CENTRE PORTION OF WALL INEFFECTIVE



EDGE OF WALL INEFFECTIVE

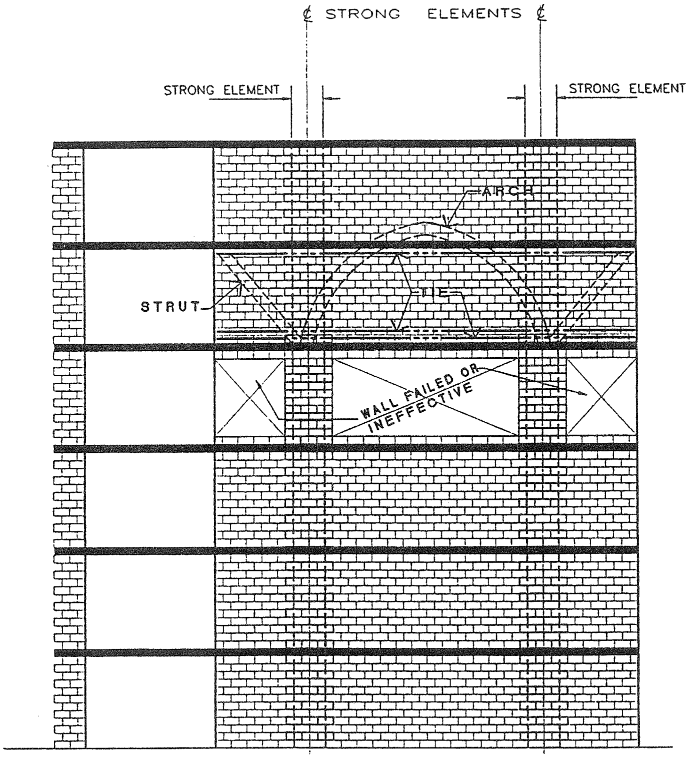
ALTERNATE PATHS

Fig. 1



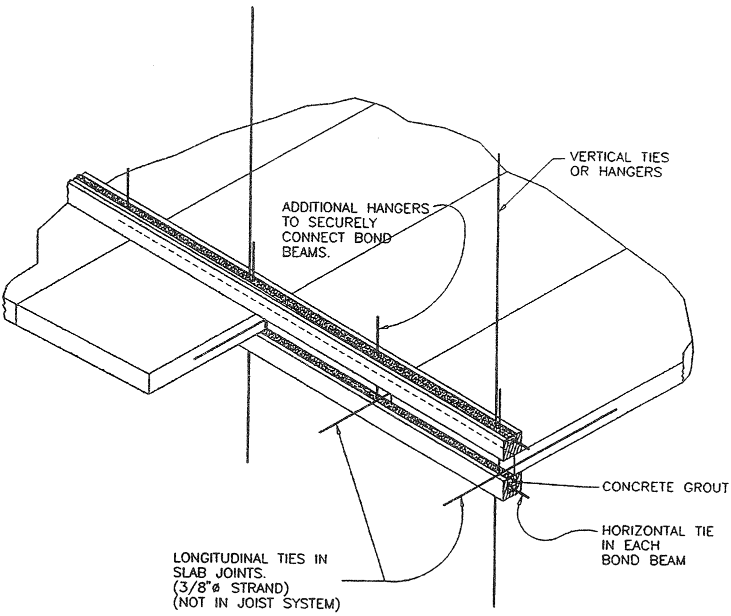
RETURN WALLS USED AS STRONG ELEMENTS

Fig. 2



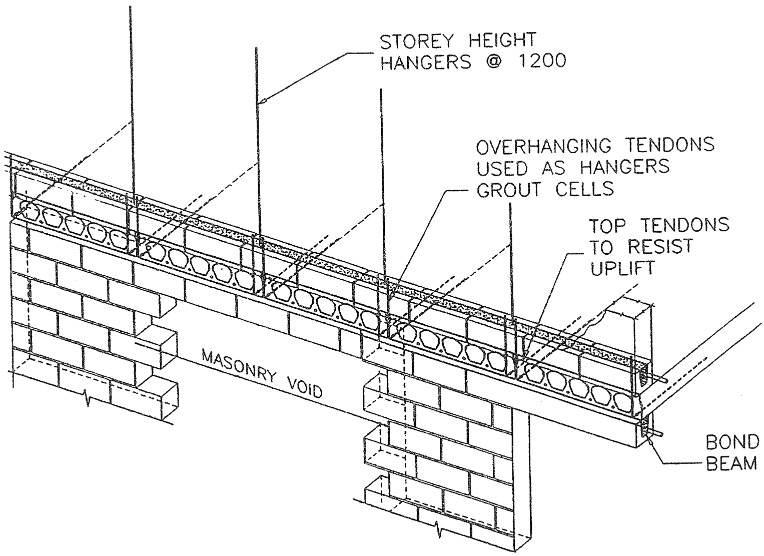
ARCHING ACTION BETWEEN STRONG ELEMENTS WITHIN WALL

Fig. 3



ESSENTIALS OF P.C. SLAB CONNECTIONS AT INTERIOR WALL

Fig. 4



EXTERIOR WALL DETAIL

Fig. 5

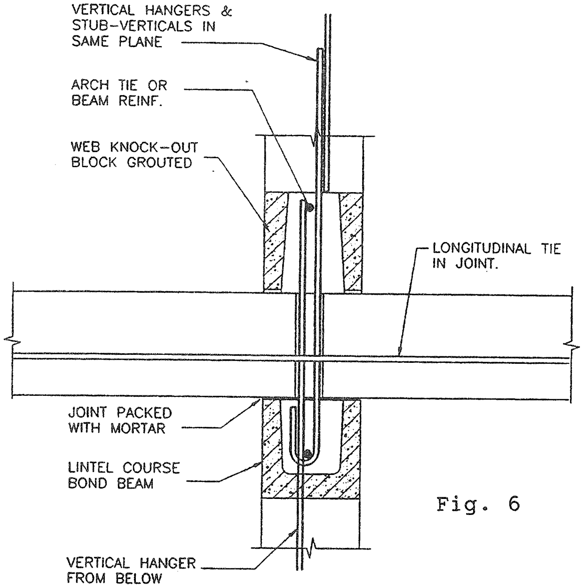


Fig. 6

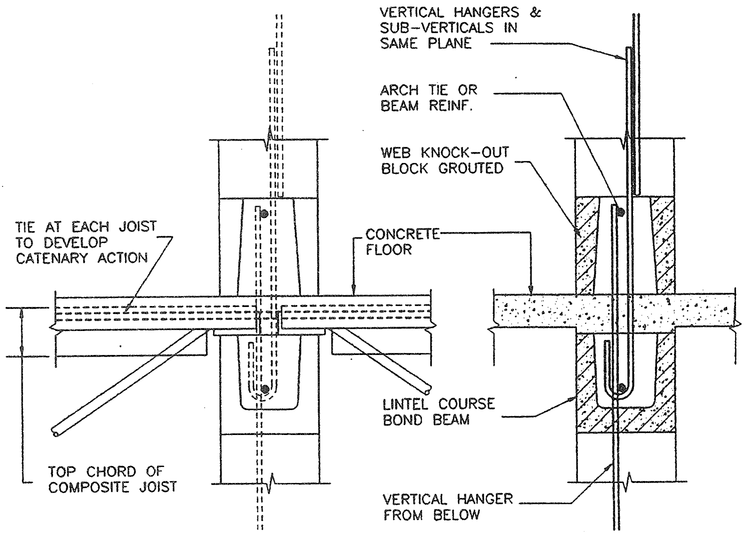


Fig. 7

SECTION AT JOISTS SECTION BETWEEN JOISTS