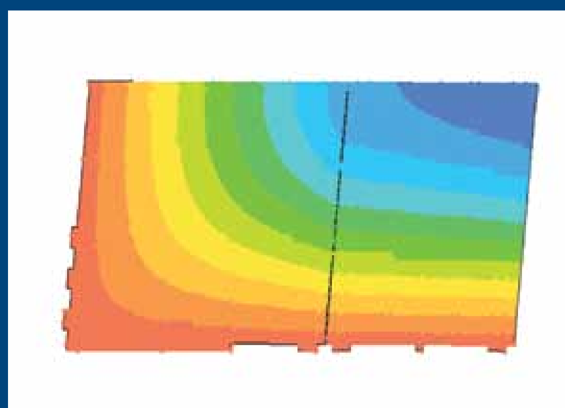
HANDBOOK FOR THE STRUCTURAL ASSESSMENT OF LARGE PANEL SYSTEM (LPS) DWELLING BLOCKS FOR ACCIDENTAL LOADING

Stuart Matthews and Barry Reeves



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or
IHS BRE Press
Willoughby Road
Bracknell RG12 8FB
Tel: 01344 328038
Fax: 01344 328005
Email: brepress@ihs.com

Printed in Great Britain using material containing a minimum of 75% post-consumer waste and the remainder 25% ECF pulp

Index compiled by Paul Nash

BR 511

First published 2012
ISBN 978-1-84806-200-9

PREFACE

The progressive collapse of part of Ronan Point in 1968 has clearly proved to be a very significant event not only in the history of structural engineering but also in terms of some of the central tenets of contemporary structural engineering philosophy, particularly to the ongoing and relevant discussions on matters concerning disproportionate damage and associated topics. However, it is in the nature of things that, with the passage of time, priorities change and past events feature less prominently in people's consciousness. Those unfamiliar with the Ronan Point incident may be unaware of the origin of some of today's performance requirements and the associated provisions, which need to be made.

This Handbook seeks to counter this trend by bringing together the relevant background information and putting it into the context of current performance expectations. It does this by providing insight into the evolution of the Building Regulations and the current Requirement A3 of *Approved Document A – Structure*[1]. This is supported by a review of the available statistical data for the hazard environment within which large panel system (LPS) dwelling blocks exist, linking this information to contemporary risk assessment and management concepts (ie ALARP/SFARP principles) to allow the adoption of rational risk-based strategies in order to facilitate a more unified and consistent approach to the assessment and through-life management of this class of buildings.

The existing guidance used for the structural assessment of LPS dwelling blocks for accidental loading is the Ministry of Housing and Local Government Circulars 62/68[2] and 71/68[3], which were produced shortly after the partial collapse of Ronan Point in 1968. It is necessary to update this guidance, not only to account for subsequent BRE work involving full-scale load testing in three LPS dwelling blocks and the general development of assessment methodologies, but also to make the guidance consistent with the approach to accidental actions employed in the structural Eurocodes and the general philosophical approach employed in contemporary risk management.

This Handbook is intended for engineers involved in the structural assessment of existing multi-storey LPS dwelling blocks, and a structural assessment methodology for this class of building is outlined in section 12. A risk-based methodology for structural assessment of LPS dwelling blocks and through-life management is presented, which has a particular focus upon accidental loads and actions.

The guidance given in this Handbook is necessarily general. It will be necessary for engineers to interpret and apply the information presented, together with the associated recommendations, to the particular circumstances of the LPS dwelling block being appraised on the basis of their engineering experience and judgement. This Handbook contains a large amount of supporting background information, some of which is highly specialised. It may be appropriate to seek specialist advice upon aspects of undertaking risk assessments and/or hazard identification.

In summary, this Handbook:

- Defines a set of requirements for LPS dwelling blocks exceeding four storeys in height (ie five storeys and higher), which are to be used to ascertain whether such LPS dwelling blocks are considered to satisfy Requirement A3 of *Approved Document A – Structure*[1].
- Presents a historical review of key events that have occurred since the partial collapse of Ronan Point in 1968 and details the associated evolution of requirements relating to disproportionate damage and associated matters as set down in *Approved Document A - Structure,* including the introduction of the structural Eurocodes.
- Reviews the hazards to which LPS dwelling blocks are exposed, and evaluates the foreseeable risks associated with accidental loadings and actions to which such blocks may be exposed. Justification is given for the 17 kN/m^2 accidental overpressure loading criterion used in the structural assessment of LPS dwelling blocks without a piped gas supply and without a basement. The risks associated with vehicular impacts and accidental external gas explosions are also considered.
- Describes recent structural tests on three LPS dwelling blocks undertaken by BRE, together with a range of earlier structural tests performed by others, which give insight into the potential behaviour of LPS dwelling blocks under accidental loadings and actions. The BRE tests, which were preceded by forensic investigations of the blocks concerned, included a variety of structural tests simulating overpressure loading (simultaneous loading of walls and floors) taken to failure to assess the strength and performance of the structural members forming the walls and floors of the test rooms. There was an associated test involving breaking the load path to the foundations

of a loadbearing kitchen–lounge spine wall in a Bison Wallframe LPS dwelling block. This involved removal of the top section of one of these walls, with 14 storeys remaining above the test location, demonstrating that alternative load paths were mobilised. This work was complemented by finite element and other forms of structural analysis.

- Sets out the basic principles and steps of a methodology for the assessment of large panel buildings subject to accidental loading and actions, drawing upon a range of structural assessment techniques involving increasing degrees of sophistication/complexity.
- Describes options for undertaking strengthening and other preventive or remedial works on LPS dwelling blocks, should the structural assessment procedure be unable to justify the adequacy of the LPS dwelling block concerned for the accidental loads and actions considered.
- Contains a number of case studies, which illustrate some structural assessments that have been undertaken on LPS dwelling blocks by BRE and other consultants.

The approach adopted by BRE utilises the concept that all LPS dwelling blocks should be managed using a systematic risk assessment methodology to guide through-life management activities and associated structure related actions, with the goal of:

- eliminating hazards where practicable, and
- reducing hazards and controlling risks to the structure of these buildings as far as is practicable,

consistent with ALARP/SFARP principles, taking account that risks associated with structural damage and collapse are generally at very low levels/acceptable levels[1].

In this context through-life management activities would be expected to form part of an overall asset management system[2] operated by the owning body or authority.

This Handbook has been written primarily from the perspective of *The Building Regulations 2010*[4] for England and Wales. However, it should be recognised that Scotland and Northern Ireland are governed by separate legislation. Whilst the general objectives and requirements are similar, there are subtle differences. In spite of this, the principles involved will be generally applicable.

This Handbook comprises 13 main sections and associated supporting information, glossary, etc.

Section 1 provides an introduction and sets out the scope of this Handbook.

Section 2 describes the requirements which are to be used as a basis for the structural assessment of LPS dwelling blocks exceeding four storeys in height (ie five storeys and higher) for accidental loading.

Section 3 summarises the evolution of the Building Regulations and LPS dwelling block structural assessment requirements associated with issues of progressive collapse and related matters.

Section 4 describes the wider context of through-life performance and assessment issues relating to LPS dwelling blocks, setting down the underlying premise of the structural assessment methodology developed by BRE for LPS dwelling blocks.

Section 5 considers the nature of the hazards which experience indicates apply to LPS dwelling blocks in the UK. The principal accidental loads and actions are internal and external gas explosions, impacts by various forms of vehicle and fire. The section also provides an overview of some of the available statistics on explosions and associated hazards.

Section 6 examines risk issues and the use of risk assessment procedures in the through-life decision-making process for LPS dwelling blocks, in particular the use of the ALARP and SFARP principles. The section provides a brief overview of risk issues applicable to LPS dwelling blocks.

Section 7 explains the origin of current national assessment overpressure criteria associated with internal gas explosions; namely the 17 kN/m^2 criterion for LPS dwelling blocks without a piped gas supply and the 34 kN/m^2 criterion for LPS dwelling blocks with a piped gas supply.

Section 8 provides an overview of the structural performance of three LPS dwellings blocks as evaluated by recent full-scale load tests carried out by BRE. These tests included a number of room overpressure tests up to the ultimate load condition which applied static loadings seeking to create forces comparable to those produced by accidental internal gas explosions involving cylinder gas or other gaseous substances. An element removal test involving breaking the load path in a wall panel with 14 storeys of building above was undertaken to establish if an alternative load path would be mobilised.

Section 9 discusses a number of factors which might potentially influence the behaviour of an LPS dwelling block under accidental loads or actions and which it might be appropriate to take account of during a structural assessment.

Section 10 gives consideration to a number of other factors concerned with the durability of concrete components forming an LPS dwelling block, undertaking a structural assessment after a severe fire and the risk of progressive collapse during demolition at the end of the useful life of the block.

Section 11 provides a summary of the requirements, hazards, risks and through-life performance issues affecting an LPS dwelling block.

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[1] In this document reference is made to managing risks on the basis of ALARP principles, that is seeking to ensure that risks are '*as low as reasonably practicable*'. The term ALARP is used widely in the technical literature and associated guidance. However, an alternative term that is commonly used in legislation is SFARP: '*so far as is reasonably practicable*'. In this document where reference is made to the term ALARP, this should also be taken to include the alternative SFARP

[2] Asset management is a process of providing planned through-life care for constructed assets; it involves management and planning procedures together with the associated maintenance, preventive and/or remedial works activities. Asset management activities/systems involve the planning and financial aspects required to ensure that the appropriate resources are available for the associated maintenance, preventive and/or remedial works activities that may be necessary. In this document terms such as '*through-life care*', '*planned through-life care*' and '*through-life management activities*' imply linkage to an overarching asset management scheme.

Section 12 sets down a methodology for assessing LPS dwelling blocks for accidental loads and actions.

Section 13 outlines potential strengthening options for LPS dwelling blocks and describes a methodology for the development of a strengthening/through-life management strategy for an LPS dwelling block.

Section 14 presents some concluding comments. Attention is drawn to the potential vulnerability of LPS dwelling blocks to progressive collapse. This could occur should a sufficiently large explosion or devastating incident occur, creating forces which exceed the *collapse resistance* of the LPS dwelling block. The recent progressive collapse of parts of a number of LPS dwelling blocks during demolition highlights this risk, particularly for poorly constructed blocks with deficient tying.

The above mentioned material is supported by an extensive reference list and bibliography.

There are also 11 Appendices to this Handbook. These present an overview of a number of key subject areas including the historical background to LPS dwelling blocks within the UK and associated guidance, together with a summary of previously unpublished information on load testing undertaken on LPS dwelling blocks or assemblies of components, spanning the last three and a half decades. The focus is upon full-scale load tests undertaken on LPS dwelling blocks by BRE over about the last decade.

Summary information is also included on various strengthening techniques that have previously been employed to enhance the strength and/or robustness of LPS dwelling blocks.

Case histories of several consultancy commissions have been included to demonstrate the various approaches that have been adopted by BRE and by other consultants when assessing various types of LPS buildings. A number of these case histories also include references to the remedial and/or strengthening works techniques that were adopted.

The 11 Appendices are titled:

Appendix A: Development of 'regulatory' requirements
Appendix B: Hazard environment
Appendix C: Risk issues
Appendix D: Outline historical review of LPS dwelling blocks in the UK since 1968
Appendix E: BRE tests on LPS dwelling blocks and laboratory structures undertaken before 2000
Appendix F: Overview of finite element analyses and calibration exercises for the 1990s' BRE load tests on LPS dwelling blocks
Appendix G: BRE load testing of a Bison Wallframe LPS dwelling block, Liverpool
Appendix H: Overview of finite element analyses and calibration exercises for the Liverpool Bison Wallframe LPS dwelling block tested by BRE
Appendix I: Strengthening options
Appendix J: LPS dwelling block assessment case studies
Appendix K: BRE trials to determine coefficient of friction at base of wall panels

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November 2011

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3 Ministry of Housing and Local Government (MHLG). Flats constructed with precast concrete panels. Appraisal and strengthening of existing high blocks: Design of new blocks MHLG Circular 71/68. London, MHLG, December 1968.

4 Department for Communities and Local Government (DCLG). The Building Regulations 2010 (England and Wales). London, TSO, 2010.

ACKNOWLEDGEMENTS

THIS PROJECT

This document is an outcome of a project sponsored by the Department of Communities and Local Government (DCLG) for the development of an informative Handbook explaining how to undertake the tasks necessary to address the technical requirements for the structural assessment of large panel system (LPS) dwelling blocks. This document is that informative Handbook. The support provided by the DCLG for this work is gratefully acknowledged.

The authors wish to acknowledge the essential contributions made by current and former BRE colleagues, especially Julie Bregulla, David Brooke, Gerard Canisius, Brian Ellis, Jesper Friis, Haig Gulvanessian, Robert Mobbs, Rohan Rupasinghe and Susanne Woodman, in respect of the current project and the previous *Partners in Innovation* and DETR research projects.

The authors also wish to recognise the valuable contributions made to the project in terms of information provided, experiences shared and review of project deliverables by the previous project partners and steering group. The authors are particularly grateful to have been able to draw freely upon these contributions and acknowledge the valuable assistance that this material has given in the preparation of this document.

The authors are also particularly indebted to a number of colleagues who undertook the task of making independent reviews of this output, namely Professor Michael Baker (Emeritus Professor of Safety Engineering, School of Engineering, University of Aberdeen), Mr John Carpenter (Secretary to SCOSS), Mr Nick Clarke (IHS BRE Press), Mrs Sarah Fray (Director of Engineering at ISE), Mr Alistair Soane (Director CROSS), and Mr Peter Watt (Project Officer at DCLG).

PREVIOUS BRE RESEARCH PROJECTS

This report has been developed from the final output of a Department for Trade and Industry (DTI) part-funded *Partners in Innovation* research project aimed at improving the management of ageing assets by the use of advanced techniques to undertake structural assessment of existing multi-storey LPS dwelling blocks for accidental loading due to non-piped gas explosions.

This document draws on work undertaken in several research projects. The most recent work involved full-scale structural load tests up to failure within a Bison LPS dwelling block situated in Liverpool, which was carried out under the (previous) Partners in Innovation (PII) scheme via a project entitled ‘Improving the management of ageing assets by advanced techniques for assessing existing multi-storey LPS blocks’. Reference is also made to the results of an earlier programme of full-scale structural loading tests upon LPS dwelling blocks which were situated in Sandwell (a Bison LPS dwelling block) and Leeds (a Reema Conclad LPS dwelling block).

The authors gratefully acknowledge the support provided by the DTI and the project partners who are listed below, and that given by the then Department of the Environment, Transport and the Regions (DETR) for the earlier experimental work.

PREVIOUS LPS PII PROJECT PARTNERS

Consulting engineers

- Alan Conisbee and Associates
- Campbell Reith Hill
- Carter Clack
- Curtins Consulting
- Ian Bennett Associates
- Mitchell McFarlane and Partners

Local authorities and housing associations

- Association for Structural Engineers of London Boroughs (ASELB) via London Borough of Bromley
- Birmingham City Council
- CityWest Homes (London Borough of Westminster)
- Flintshire County Council
- Liverpool Housing Action Trust (who kindly provided an LPS dwelling block for testing)
- London Borough of Barking & Dagenham
- London Borough of Enfield
- London Borough of Greenwich
- London Borough of Hackney
- London Borough of Lambeth
- London Borough of Sutton
- Northern Ireland Housing Executive
- Sandwell Metropolitan Borough Council
- Stockport Borough Council
- Sunderland Housing Group

Industrial companies

- Birmingham City Laboratories
- Germann Instruments
- Wilde and Partners/TNO (Netherlands Organisation for Applied Scientific Research)

PREVIOUS LPS PII PROJECT FUNDING PARTNERS

- Department of Trade and Industry
- Flintshire County Council
- Northern Ireland Housing Executive

EARLIER DETR LPS RESEARCH PROJECT COLLABORATION PARTNERS

- Leeds City Council (who kindly provided an LPS dwelling block for testing)
- Sandwell Metropolitan Borough Council (who kindly provided an LPS dwelling block for testing)

CONTENTS

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APPENDIX J: LPS DWELLING BLOCK ASSESSMENT CASE STUDIES (Cont'd)

EXECUTIVE SUMMARY

Background – Ronan Point and the evolution in technical requirements. Since the progressive collapse of part of Ronan Point following an internal gas explosion in 1968, LPS dwelling blocks have effectively been treated as a special class of UK building. Requirements for their structural assessment for normal and accidental loads have been given in Ministry of Housing and Local Government (MHLG) Circulars 62/68[1] and 71/68[2], both of which were titled *Flats constructed with precast concrete panels. Appraisal and strengthening of existing blocks: Design of new blocks*. Later BRE Report 107: Part 2[3] gave additional guidance on the structural adequacy and durability of LPS dwelling blocks. MHLG Circulars 62/68[1] and 71/68[2] published in 1968, along with various other related guidance from that era, were never withdrawn and notionally remain in force today. However, that guidance has become outdated by subsequent technical developments in structural assessment procedures, and by changes in the philosophy behind regulatory requirements and how this has been embodied in new codes of practice, such as the Eurocodes. This Handbook provides revised technical performance requirements (in section 2) and associated structural assessment guidance.

Reasons for undertaking the programme of LPS dwelling block work and producing revised guidance for structural assessment. In the early and mid-1990s LPS dwelling blocks were being appraised, some after more than 30 years in service. BRE found that extensive strengthening works were often being recommended. In a number of instances these appeared to offer only marginal improvement to the existing level of safety. In other instances, viable communities within LPS dwelling blocks were inadvertently destroyed when the decision was made to demolish a block because of the cost of the remedial and related works that were being recommended. Such outcomes, whilst following the guidance available at the time, were judged to offer not only poor value for money but were resulting in what seemed to be unjustified outcomes. Thus there was a need to better-establish the actual performance of LPS dwelling blocks under accidental loads, as well as improving and updating the guidance for the structural assessment of this particular class of buildings.

Types of accidental loading, sources of hazard and benchmarking of risks. A review was made of the hazards to which LPS dwelling blocks are exposed and the associated risks. These hazards include internal and external gas explosions and fire, as well as potential vehicular impacts arising from road vehicles, trains and aircraft. The annual probability of occurrence of these extreme events was found to be very small; details are given in section 6. The review also examined the maximum overpressure likely to be generated during an internal gas explosion. It was found that some explosions involving a piped gas supply had the potential to be significantly more devastating than those not involving a piped gas supply. It was established that for situations where a piped gas supply was not involved in an internal gas explosion, an overpressure of 17 kN/m^2 formed a reasonable assessment criterion. Conversely, where a piped-gas supply is present in any part of a building, or where it contains a basement or other poorly-ventilated zone where gas from an external source could accumulate, the assessment overpressure criterion should be 34 kN/m^2.

BRE programme of load testing existing LPS dwelling blocks. This established that, for the LPS dwelling blocks tested, member capacities were compatible with the loads applicable to circumstances where a piped-gas supply is not present in any part of the building (ie the wall and floor panels in the LPS blocks tested were able to resist an overpressure in excess of 17 kN/m^2). In the LPS dwelling blocks tested by BRE, the load bearing wall panels generally failed by translation (lateral shear) at the bottom of the wall panels (ie the wall panels performed satisfactorily in bending). The floor slabs failed in bending under the applied load (ie they performed satisfactorily in shear).

Requirements against which LPS dwelling blocks are to be evaluated. An LPS dwelling block exceeding four storeys in height (ie five storeys and higher) will be considered to satisfy Requirement A3 of *Approved Document A – Structure*[4] if it meets one of the following:

LPS Criterion 1: There is adequate provision of horizontal and vertical ties to comply with the current requirements for Class 2B buildings as set down in the codes and standards quoted in *Approved Document A – Structure*[4] as meeting the requirements of *The Building Regulations*.

LPS Criterion 2: An adequate '*collapse resistance*' can be demonstrated for the foreseeable accidental loads and actions as defined below.

LPS Criterion 3: Alternative paths of support can be mobilised to carry the load, assuming the removal of a critical section of the load bearing wall in the manner defined for Class 2B buildings in *Approved Document A – Structure*[4] or alternatively assuming the removal of adjacent floor slabs (taking the floor slabs bearing on one side of the wall at a time) providing lateral stability to the critical section of the load bearing wall being considered.

Collapse resistance of LPS dwelling block structural elements and the associated load transmitting joints between the structural elements should be evaluated for the forces associated with accidental overpressure values of 17 kN/m^2 or 34 kN/m^2 for the circumstances as defined below[1].

A. An LPS dwelling block **with** a piped gas supply within or to any part of the building: an assessment overpressure of 34 kN/m^2 should be used generally throughout the building. The overpressure should be applied simultaneously to all surfaces of the single room/bounding enclosure within which the explosion (deflagration) is considered to occur. Alternatively, the approach used for the design of 'key elements' in new buildings may be adopted[2].
B. An LPS dwelling block **with** a basement: an assessment overpressure of 34 kN/m^2 should be used in the basement and in any other zone where an explosive mixture of gas might accumulate (potentially from an external source). The overpressure should be applied simultaneously to all surfaces of the single room/bounding enclosure within which the explosion (deflagration) is considered to occur. Alternatively, the approach used for the design of 'key elements' in new buildings may be adopted[2].
C. An LPS dwelling block **without** a basement and **without** a piped gas supply to any part of the building: an assessment overpressure of 17 kN/m^2 should be used. The overpressure should be applied simultaneously to all surfaces of the single room/bounding enclosure within which the explosion (deflagration) is considered to occur. Alternatively, the approach used for the design of 'key elements' in new buildings may be adopted[2]. These requirements can be applied to the part of the dwelling block above the zone defined in Category B above.

Collapse resistance is defined as '*a measure of the ability of a structural system to resist the effects of **defined** accidental loads or actions occurring at or below a defined threshold'*.

[1] However, for reliability- based assessments it is necessary to recognise and take into account that the17 kN/m^2 (non-piped gas situations) and 34 kN/m^2 (piped gas situations) assessment criteria values may be exceeded – indeed it is necessary to estimate the probability distribution function of the complete range of possible overpressures for the respective situations.

[2] Refer Clauses 5.1d and 5.3 of *Approved Document A – Structure*[4]

Structural assessment methodology for LPS dwelling blocks. The LPS dwelling block structural assessment methodology considers both normal and accidental loads and actions, seeking to identify the plausible hazards. It makes a general evaluation of the risks arising from the various types of accidental loads and actions that such blocks may be exposed to. These hazards include internal and external gas explosions, fire, as well as potential vehicular impacts arising from road vehicles, trains and aircraft. The structural assessment methodology proposed evaluates the *collapse resistance* of the LPS dwelling block, drawing upon experience gained from full scale structural tests in existing LPS dwelling blocks and historic data gathered about previous gas explosions in the UK building stock.

This demonstrated that the structure should resist the overpressure loads which might plausibly be imposed. The historic data also indicate that the probability of structurally significant vehicular impacts to be very low, such that the associated risks might be considered to be '*regarded as insignificant and adequately controlled*'.

There are four main stages in the LPS dwelling block structural assessment methodology:

- *Assessment Stage 1* – Review of existing technical information.
- *Assessment Stage 2* – Collection of new technical information.
- *Assessment Stage 3* – Assessment of block for normal loading.
- *Assessment Stage 4* – Assessment of block for accidental loading.

The hierarchical approach to the structural assessment of LPS dwelling blocks can potentially involve the following steps, which utilise increasingly sophisticated forms of structural assessment calculation.

- *Assessment Level 1* – A deterministic linear elastic analysis (eg spreadsheet)
- *Assessment Level 2* – A deterministic non-linear finite element (or alternative) analysis
- *Assessment Level 3* – Probabilistic based calculations (structural reliability evaluation)

These and the other main steps in the overall LPS dwelling block structural assessment process are shown as a mapping in Table ES1.

Implications. In circumstances where the assessment overpressure criterion to be used is 34 kN/m^2 (eg where a piped-gas supply is present), the load bearing wall panels tend to fail the structural assessment both in bending, at the mid-height of the wall panel, and in shear at the bottom of the wall panel. This would require a considerable amount of strengthening works to be carried out, resulting in a situation which is generally considered to be not economically viable. Under an overpressure criterion of 34 kN/m^2 the floor slabs would be expected to fail the assessment both in bending and shear, again this would require an unrealistically large amount of expensive strengthening works.

Thus the general expectation is that, unless the LPS dwelling block concerned was designed and built to accommodate the overpressure criterion associated with a piped gas supply (ie 34 kN/m^2), the LPS dwelling blocks in question will not have a piped gas supply and that they will therefore be assessed for an overpressure criterion of 17 kN/m^2.

The underlying assessment concept is to seek to verify that structural failure in an LPS dwelling block is unlikely to be initiated under accidental loads and action effects. As a result the structural assessment methodology does not consider post-failure behaviour, such as the ability to mobilise an alternative load path.

However, it is important to recognise that the ability to resist the foreseeable accidental load from an internal gas explosion (deflagration) – that is having an adequate *collapse resistance* – does not remove the small risk of progressive collapse in an LPS dwelling block should a load bearing component (a '*key element*') fail or should some form of sufficiently devastating incident occur which initiates failure. In such circumstances, currently it is not entirely clear whether such a progressive collapse would be considered to be '*proportionate*' or '*disproportionate*' to the magnitude of the initiating event, bearing in mind the expected very low probability of its occurrence.

Whilst the historically observed performance of LPS dwelling blocks has in general been satisfactory and the results of the BRE load tests performed to the ultimate condition on three (uninhabited) LPS dwelling blocks (two Bison Wallframe and one Reema Conclad) were reassuring, the potential vulnerability of this form of construction has been highlighted by the recent progressive collapse of parts of a number of LPS dwelling blocks during demolition[5]. The LPS dwelling blocks concerned were pre-Ronan Point Fram Russell LPS. Limited investigation of one of the collapses by BRE suggested that the particular LPS dwelling blocks are likely to have been constructed to a poor standard. Particular points were the quality of the tying at the floor slab/cross wall panel junctions, where there was a significant lack of connection (mechanical tying) between floor panels and the cross walls forming a bay, and the lack of end bearing to the floor slabs. BRE is aware that similar LPS dwelling blocks located in another part of the UK have been deconstructed without incident.

However, these incidents do highlight the need to be cautious when making a structural assessment and the critical need for adequate invasive investigation of the nature and quality of construction achieved in individual LPS dwelling blocks before embarking upon structural calculations and other aspects of the structural assessment process.

Future circumstances. The observations in this report are made on the basis of historic data. It is necessary to look to the future and consider the potential implications of higher performance standards being applied to LPS dwelling blocks and what impact issues such as less 'leaky buildings' with their lower air leakage/air change rates might have in terms of the likelihood of the occurrence of internal gas explosions and the resulting overpressures which may be generated by them.

Table ES1: **Mapping of LPS dwelling block structural assessment activities – Main steps**

Activity	**Observation**		**Doc. section [Reference]**
Define scope of work	Agree brief and requirements for structural assessment		2, 3 [6]
Hazard identification	Review potential sources of hazard		5, 11
Risk evaluation	Influences decision making; use ALARP & SFARP principles		6, 11
Structural assessment procedures and factors influencing structural behaviour			8, 9, 12
Assessment Stage 1:	Review of existing technical information		12.5
Assessment Stage 2:	Collection of new technical information		12.6
Assessment Stage 3:	Assessment of block for normal loading		12.7
Assessment Stage 4:	Assessment of block for accidental loading or action		12.8
Overpressure loadings associated with an internal deflagration • Assessment Level 1: Deterministic linear elastic analysis • Assessment Level 2: Deterministic non-linear finite element analysis • Assessment Level 3: Probabilistic based/structural reliability calculations		Steps 1 to 21 22 23	7 Table 4 Table 5 Table 6
Post-fire evaluation	Evaluation of structural effects and remedial actions		10.4
Interventions to enhance durability and strength: Through-life care, etc.			10, 13
• Maintenance works • Durability • Strengthening	Ongoing planned periodic activities to maintain functionality Preventive and remedial durability works options Interventions to enhance strength and damage tolerance		Glossary 10.2, 10.3 13, Table 34
Through-life management, monitoring and care	• Periodic inspection, monitoring and structural assessment • Hazard identification, risk reduction and management measures; use ALARP and SFARP principles		12.9 5, 6, 12.10 Table 35
Demolition/end of life	End of life: Demolition and progressive collapse issues		10.5
Reporting of findings	Provision of report on findings and recommendations		[6]

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1 INTRODUCTION AND SCOPE OF THE HANDBOOK

1.1 BACKGROUND

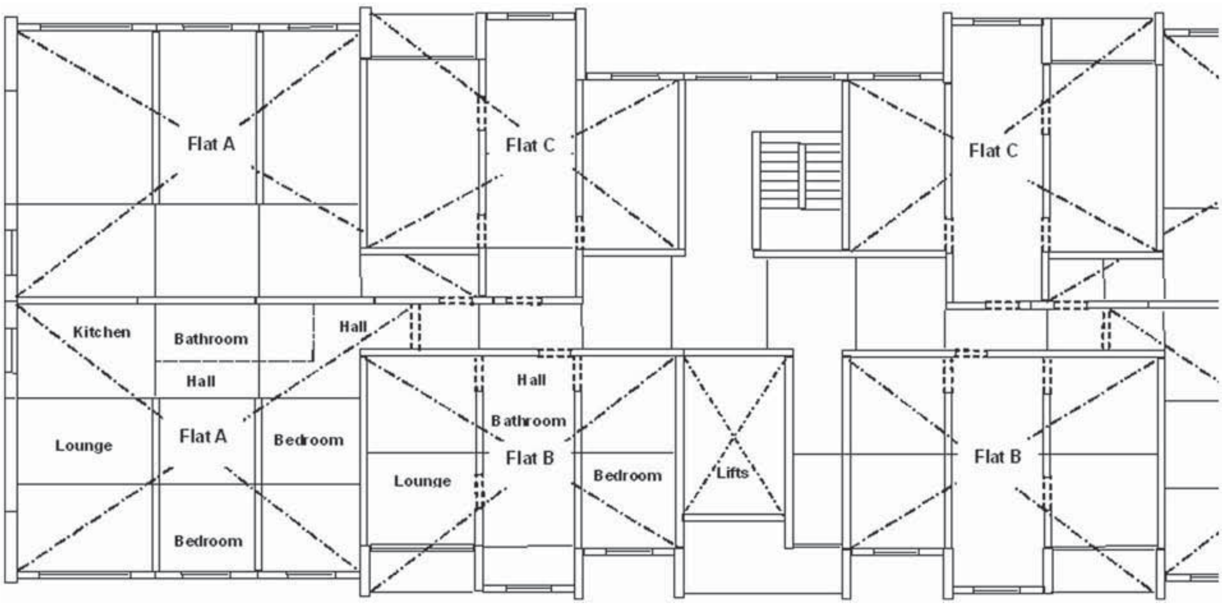
Essentially, large panel system (LPS) dwelling blocks are gravity structures, as are traditional masonry constructed buildings. LPS dwelling blocks typically comprise precast reinforced concrete floor and roof components spanning onto storey-height structural precast concrete wall panels. The precast concrete components are connected by various forms of joints made on site. Vertical loads are carried to the ground through the structural wall panels, which also provide stability against lateral loads. Walls orientated across the short dimension of the building are usually called cross-walls, or flank walls if they are the exterior walls located at the ends of the building or in re-entrant zones. The structural walls orientated along the long dimension of the building are often referred to as spine-walls.

Figures 1 and 2 illustrate two common types of LPS dwelling blocks originating from the 1960s or thereabouts. However, few people realise that large panel precast concrete construction was pioneered at about the turn of the 20th century. The Eldon Street flats in Liverpool were built using the system in 1905, with the structural form being remarkably similar to the LPS dwelling block system of building 'invented' in the 1950s. A series of three photographs showing: the transportation of the large storey-height wall panels from the precasting yard to site on a trailer towed by a coal-fired traction engine; the erection of the panels on site; and the finished three-storey building, is included in *Historic concrete – background to appraisal*, edited by Sutherland, Humm and Chrimes[1].

Figure 3 illustrates the general arrangement of the wall and floor panel construction forming a notionally typical LPS dwelling block. In reality there are significant differences in the details of the individual forms of LPS construction, which were proprietary products produced by the various manufacturers of the day. It is also common for there to be differences in aspects of the structural details employed by a particular manufacturer for buildings at different locations, reflecting specific requirements of the building owner or commissioning authority.

Figure 1: Bison LPS dwelling block
(courtesy Sandwell Metropolitan Borough Council)

Figure 2: Reema Conclad LPS dwelling block
(courtesy Leeds City Council)



Nominal floor and wall panel plan of an LPS block (part floor plan)

Figure 3: General configuration of the wall and floor panel construction forming an LPS block

The structural precast concrete wall panels in LPS blocks designed before 1968 commonly contain very little steel reinforcement[1]. Typically the wall panels contain only small amounts of peripheral 'handling steel' to accommodate stresses arising during manufacture, transport and erection. The floor components are commonly treated as spanning in one-direction between the cross-walls/flank walls. However, on some occasions floor components act as two-way spanning slabs (ie in Fram Russell LPS dwelling blocks). Although LPS dwelling blocks are understood to be constructed from reinforced concrete, it is possible (but believed to be unlikely) that prestressed concrete floor components could have been used in some LPS dwelling blocks.

In some LPS dwelling blocks the ground floor structure is formed entirely of in-situ concrete or is of precast/in-situ reinforced concrete hybrid construction.

The site-placed steel reinforcement present in the in-situ horizontal joints between wall and floor panels (see Figure 4) has no significant role in the primary structural function of transmitting vertical loads to the ground under normal loading conditions (ie gravity and wind loads).

The overall structural behaviour of LPS dwelling blocks under normal loads (eg gravity and wind, including self-weight, imposed and snow loads), thermal and ground movements, together with accidental loads, is outlined in BRE Report 107: Part 2[2].

Thus, in addition to normal loads, LPS dwelling blocks could be subject to accidental loads and actions arising from incidents such as internal or external gaseous explosions (deflagrations), fire or vehicle impact. In these circumstances the steel reinforcement within the in-situ joints may mobilise continuity forces to avoid the initiation of local failure within the LPS dwelling block.

[1] Wall panels in post-1968 LPS dwelling blocks tended to contain significantly more reinforcement compared to wall panels in similar blocks designed/built prior to 1968.

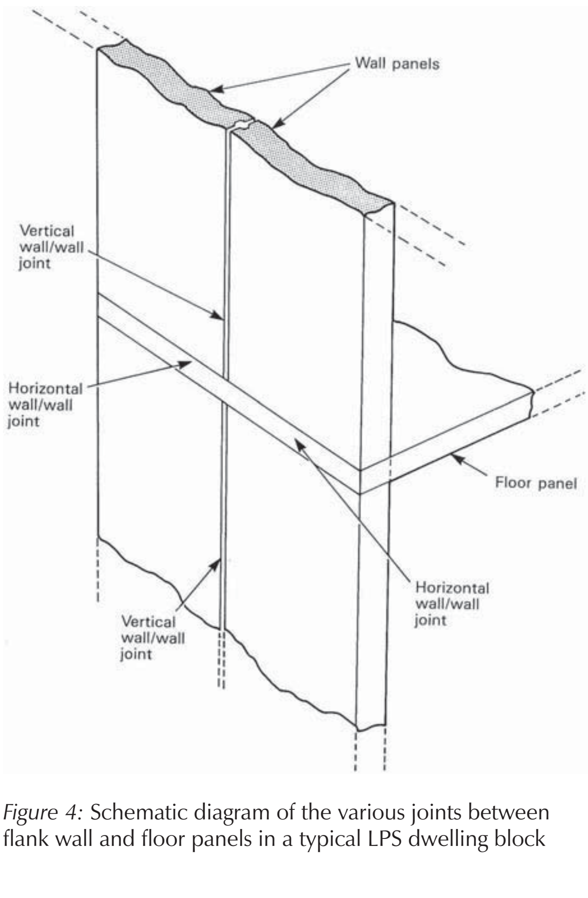


Figure 4: Schematic diagram of the various joints between flank wall and floor panels in a typical LPS dwelling block

If the accidental loads and actions are of a sufficiently large magnitude, local damage could be caused to load bearing components and/or to the in-situ joints between them. In these circumstances it would be necessary to mobilise alternative load paths to maintain the overall stability of the LPS block. Where local failure has occurred, the steel reinforcement within the in-situ joints and panels would need to have sufficient ductility and strength, plus appropriate detailing, to accommodate the potentially significant deformations and distortions created as alternative load paths are mobilised.

Whilst it also has to be recognised that LPS dwelling blocks could potentially be subject to malicious acts or attacks, such a matter is outside the scope of this document. Perhaps bizarrely, such events could be inadvertent; recent experience has shown that flats within some LPS dwelling blocks have been used by those involved in the manufacture of improvised explosive devices (IEDs). Accordingly, it may be of interest that the Home Office, through the Centre for Protection of National Infrastructure and other UK security agencies, makes available guidance on how to create safer places and buildings that are less vulnerable to terrorist attack[3].

The existing guidance used for the structural assessment of LPS dwelling blocks for accidental loading is the MHLG Circulars 62/68[4] and 71/68[5], which were produced shortly after the partial collapse of Ronan Point in 1968. It is necessary to update this guidance not only to account for subsequent BRE work involving full-scale load testing in three LPS dwelling blocks and the general development of assessment methodologies, but also to make the guidance consistent with the approach to accidental actions employed in the structural Eurocodes and the general philosophical approach employed in contemporary risk management.

It is also important to recognise that overall, the historic structural performance of LPS dwelling blocks has been satisfactory, with most of the blocks which still exist having been in service for over 40 years. In instances where internal (non-piped) gas explosions have occurred in LPS dwelling blocks, structural damage has been limited in extent, and no occupied UK LPS dwelling blocks have experienced progressive collapse or a disproportionate degree of damage in-service as a result of a gaseous explosion or a vehicle impact since the partial collapse of Ronan Point in 1968.

However, the potential vulnerability of this form of construction has been highlighted by the recent progressive collapse of parts of a number of LPS dwelling blocks during demolition[6]. The LPS dwelling blocks concerned were pre-Ronan Point Fram Russell LPS. Limited investigation of one of the collapses by BRE suggested that the LPS dwelling blocks concerned could have been constructed to a relatively poor standard. Particular points were the quality of the tying at the floor slab/cross wall panel junctions, where there was a significant lack of connection (mechanical tying) between floor panels and the cross walls forming a bay, and the lack of end bearing to the floor slabs. BRE is aware that similar LPS dwelling blocks located in another part of the UK have been successfully deconstructed without incident. However, these collapses do highlight the need to be cautious when making a structural assessment, and the critical need for adequate invasive investigation of the nature and quality of construction achieved in individual LPS dwelling blocks before embarking upon extensive structural calculations in the structural assessment process.

Similarly, progressive collapse could also occur should a sufficiently large explosion or devastating incident occur which created forces which exceed the *collapse resistance* of the LPS dwelling block. In-service deterioration could adversely affect collapse resistance.

However, full-scale structural load tests by BRE to the ultimate load condition in three LPS dwelling blocks have demonstrated that this form of construction is stronger than the traditional 'simplified' structural calculations used to assess their response to accidental loading could demonstrate. Thus the LPS dwelling blocks tested by BRE have proved able to resist the forces due to (severe) internal gas explosions, thereby avoiding the initiation of element and structure failure which might have lead to progressive collapse or a disproportionate degree of damage. The condition of these three LPS dwelling blocks was judged to be 'reasonable' following detailed invasive forensic investigations of their construction. These investigations revealed that the three LPS dwelling blocks did contain a variety of construction 'faults', typical of those encountered with this form of construction. Thus the three LPS dwelling blocks tested were considered to be reasonably representative of those found in the overall population of LPS dwelling blocks.

In addition, assessments undertaken following the existing guidance[4,5] have sometimes produced unexpected and inconsistent results. For example, some engineering consultants chose to ignore certain facets of structural behaviour which other consultants would take into account and, if incorporated into the assessment process, would in many instances have been able to demonstrate adequate reserves of strength against the specified accidental loading.

This work takes advantage of the outcomes of a previous DTI PII funded research project involving full-scale structural load tests to the ultimate load condition in three LPS dwelling blocks.

It is estimated that there are in excess of 700 individual high rise LPS dwelling blocks (circa 50,000 individual dwellings), plus over 1000 low- and medium-rise LPS dwelling blocks in the UK.

Whilst this Handbook is essentially concerned with LPS dwelling blocks, the outcomes and the assessment methodologies described may be applicable to other forms of LPS buildings.

It should be noted that this Handbook has been written primarily from the perspective of *The Building Regulations 2010*[7] for England and Wales. However, it should be recognised that Scotland and Northern Ireland are governed by separate legislation. Whilst the general objectives and requirements are similar, there are subtle differences. In spite of this the principles involved will be generally applicable.

1.2 AIMS AND OBJECTIVES OF THE CURRENT PROJECT

The overall aim of this project has been to produce new guidance for the structural assessment of existing LPS dwelling blocks, focusing primarily upon their resistance to accidental loading associated with gaseous explosions (deflagrations) occurring within buildings –

particularly those without a piped gas supply and without a basement[2]. This guidance does not address malicious attacks or overpressure loadings associated with the detonation of high explosives (ie blast loads are excluded).

MHLG Circulars 62/68[4] and 71/68[5] published in 1968, along with various other related guidance from that era, were never withdrawn and notionally remain in force today. However, that guidance has become outdated by subsequent technical developments in structural assessment procedures, and by changes in the philosophy behind regulatory requirements and how this has been embodied in new codes of practice, such as the suite of Eurocodes. This Handbook provides revised technical performance requirements (in section 2) and associated structural assessment guidance.

1.3 RELATED BRE RESEARCH STUDIES

This Handbook draws on the final output report of a DTI part-funded *Partners in Innovation* research project. The aim of that research project was to improve the management of ageing assets by the use of advanced techniques to undertake structural assessment of existing multi-storey LPS dwelling blocks for accidental loading associated with what have been termed non-piped gas explosions[3].

This Handbook draws on work undertaken in several research projects. The most recent work involved full-scale structural load tests up to failure within a Bison LPS dwelling block situated in Liverpool, which was carried out under the (previous) PII scheme via a project entitled '*Improving the management of ageing assets by advanced techniques for assessing existing multi-storey LPS blocks*'. Reference is also made to the results of an earlier programme of full-scale structural loading tests upon LPS dwelling blocks which were situated in Sandwell (a Bison LPS dwelling block) and Leeds (a Reema Conclad LPS dwelling block).

The final outputs from the previous DTI project were:

- An outline historical summary of key events that have occurred within the UK with respect to large panel structures (LPS) including the partial collapse of Ronan Point in 1968, together with the changes that have taken place in the technical requirements with respect to LPS dwelling blocks following the Ronan Point Inquiry.
- An overview of the risk environment that LPS dwelling blocks may be subjected to and a brief summary of the mechanisms associated with piped and non-piped gas explosions.
- A summary of the results of a series of a limited number of gas explosion tests and full-scale static tests undertaken on joint 'mock-ups' and, more recently, complete buildings.
- Selected case studies of previous structural assessments of LPS dwelling blocks.

The work highlighted a number of inconsistencies in assumptions and approaches used in current structural assessments which previously have resulted in widely differing conclusions about the suitability of existing LPS dwelling blocks for continued service and in the associated management strategies adopted. This earlier work also confirmed that there was a need to incorporate the findings of the DTI project and that of related engineering assessments and studies of LPS dwelling blocks into current guidance documents covering the assessment of LPS dwelling blocks under accidental loading.

The programme of work described in this Handbook was undertaken to resolve these issues.

1.4 PREVIOUS BRE WORK ON LPS DWELLING BLOCKS

In the mid-1980s BRE undertook a programme of investigations and other work relating to LPS dwelling block systems. This resulted in a series of BRE reports (see bibliography) of which BRE Report 107: *The structural adequacy and durability of large panel system dwellings*[2] is most pertinent to the current considerations. This reported upon site investigations of construction carried out upon examples of eleven LPS dwelling block systems (in Part 1) and provides general guidance on assessment of LPS dwelling blocks (in Part 2). These reports complement earlier work concerning Taylor Woodrow-Anglian (TWA) LPS dwelling blocks[8]; of which Ronan Point was an example.

BRE Report 107: Part 1 - *Investigations of construction*[2] describes the findings of visual inspections and the physical opening-up of joints at some 70 locations in the various blocks examined; together with some 400 determinations of carbonation depths and chloride contents. Additional information was obtained from investigative reports produced by consultants. Useful details provided concern:

- Reinforcement provision and condition within joints between precast concrete components.
- Reinforcement provision and condition within precast components and in-situ concrete joints.
- The nature and condition of the concrete and dry-pack mortar within in-situ joints.
- The security of parapet panels.

BRE Report 107: Part 2 - *Guidance on appraisal*[2] provides recommendations for sampling and inspection of joints and structural connections, as well as structural assessment for normal and accidental loads.

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[2] Refer to the requirements described in section 2.

[3] A non-piped gas explosion refers to an accidental deflagration which arises from the ignition of a build-up of flammable gas in a building or other enclosed space due to leakage from a source other than a piped gas supply. This implies that the build-up of flammable gas which can occur in a poorly ventilated enclosure is limited and is unlikely to result in a deflagration more violent than that associated with a 'severe' explosion. These matters are discussed in section 5.

HANDBOOK FOR THE STRUCTURAL ASSESSMENT OF LARGE PANEL SYSTEM (LPS) DWELLING BLOCKS FOR ACCIDENTAL LOADING

This handbook presents new guidance on the structural assessment and strengthening options for large panel system (LPS) dwelling blocks, focusing primarily on their resistance to accidental loading associated with gas explosions, and supported by extensive background information.

The progressive collapse of part of Ronan Point tower block in east London in 1968 was a significant event in structural engineering in relation to the understanding of disproportionate damage to structures. Extensive research and investigations since then, including full-scale structural load tests on a block in Liverpool, are taken fully into account.

This handbook:

- defines the requirements to be met and the criteria against which the results of a structural assessment of this particular class of building should be judged. These are seen to effectively supersede the previous guidance set down in the Ministry of Housing and Local Government Circulars dating back to 1968
- gives guidance on how to undertake the structural assessments which are required, drawing on previously unpublished technical information
- details the historic background to these requirements, with these being brought up to date and set in the contemporary philosophical context of the requirements of the recently introduced structural Eurocodes
- explains the risk environment which applies to this class of building
- provides an overview of durability assessment/intervention and strengthening options.

IHS BRE Press, Willoughby Road
Bracknell, Berkshire RG12 8FB
www.brebookshop.com
BR 511

ISBN 978-1-84806-200-9
9 781848 062009