Full Scale Fire test on a Post Tensioned Slab

By Dr. Fergal Kelly

Reinforced concrete structures in fire: a review of current rules

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Synopsis
This review of current design rules for fire resistance of reinforced concrete structures examines many of the assumptions on which these rules are based and presents evidence suggesting that the rules may be inadequate both for the assessment of the effects of spalling and the prevention of collapse. Initially it reviews the consequences of spalling on the performance of key concrete elements within a structure before describing effects which occur in complete structures that are not apparent from standard fire tests. This includes a review of fire incidents in real buildings, a compartment fire test carried out on the concrete frame at BRE Cardington, and a comparison with numerical models of concrete in fire. Results are also presented from a recent furnace test on a restrained post-tensioned slab. It concludes with a call for a fundamental review of the basis of the current rules and a programme of testing of modern structural components.

Notation

A_c	Concrete cross sectional area
A_s	Reinforcement cross sectional area
f_{ck}	Concrete cylinder strength
f_y	Reinforcement strength
$N_{Ed,fi}$	Axial load in the fire limit state
N	Load ratio
t_{BS8110}	Fire resistance period in accordance with BS 8110 Part 2
t_{fr}	Experimental fire resistance period
α_{cc}	Concrete load duration factor
ω	Mechanical reinforcement ratio

Introduction
High strength and self-compacting concrete is not considered in this paper as the incidence of spalling, and the necessary mitigating measures, are well documented[1].

Significance of the spalling of structural elements
Although the occurrence of concrete spalling is linked to moisture content, the assumption that there is a safe, or critical, moisture content level below which spalling will not occur is difficult to justify. Historically, this concept dates from work by Meyer-Ottens in the early 1970s[2] when the experimental work carried out on single specimens established the idea of a critical moisture content. Although the study included the effect of stress due to applied load, the effect of varying permeability could not be assessed[3]. Recent simulation work on spalling[4] has clearly indicated that a combination of moisture content and permeability contribute to the occurrence of spalling.

Flat slabs and columns are considered to be the structural elements most susceptible to the effects of excessive spalling and it is mainly these elements which are considered in this paper. With regard to other structural elements, furnace tests carried out on continuous waffle slabs by CIRIA[5], indicated that loss of cover due to spalling may not to be critical on ribbed slabs. Beams, unless lightly reinforced with a single bar at each of the corners in the soffit, are also less likely to be critically affected by spalling as any middle bars in the bottom layer (and any subsequent layers) will be less affected by temperature rise even when spalling occurs. This can be demonstrated by numerical calculations on heat transfer[6]. These forms of construction may however be susceptible to other failure mechanisms which are discussed in this paper.

Continuous post-tensioned flat slabs
Van Herberhen and Van Damme[7] reported the results from eight fire tests on continuous post-tensioned flat slabs with unbonded tendons. The slabs were 180mm thick, one way spanning, cantilevered over the supports and loaded on the

Keywords: Reinforced concrete, Spalling, Post tensioned, Flat slabs, Columns, BS 8110, Buildings, Fire tests, Numerical Modelling

Table 1: Fire test data on continuous flat slabs

Slab no	internal span (m)	cantilever span (m)	aggregate	cover (mm)	age (days)	t_f (min)	t_{BS8110} (min)
P1	6	2	Gravel	20	273	59	60
P2	6	2	Gravel	30	280	40	120-180
P3	6	2	Gravel	30	274	71	120-180
P4	6	1.8	Gravel	32.5	98	56	120-180
P5	6	1.8	Limestone	32.5	169	150	120-180
P6	6	1.8	Limestone	32.5	126	224	>240
P7	6	1.5	Gravel	40	107	86	120-180
P8	6	1.5	Gravel	40	104	109	120-180

NOTES:
Slab P1: Complete collapse at 69 minutes. No explanation is given by the authors between the figure of 59 in the results and as comment of complete collapse at 69 mins
Slab P2: Test was terminated at 40 minutes owing to excessive rates of deflection
Slab P3: Slab collapsed at 71 mins
Slab P4: Excessive spalling, test terminated in view of collapse risk
Slab P5: Large amounts of spalling, test terminated
Slab P6: As P5
Slab P7: Test problems involving restart, large amounts of transverse cracking
Slab P8: Secondary reinforcement visible after test, test terminated at incipient collapse

Ranges are quoted under t_{BS8110} where the actual cover lies between the tabulated values. Note that none of the slabs with the exception of slab P5 (which had limestone aggregate) complies with the detailing rules from BS 8110: Part 2.

Introduction

- Background
  - Increasing workload with PT slabs
  - Concerns voiced by suppliers
- Historical research
  - Surveys, large scale tests, numerical models
- Fire test on PT Slab
  - Configuration, results
- Overview and Conclusions
  - Further Testing

Background

- Development of concrete cover
  - BRE Study 1936-46
  - 13-64 mm cover (CP114 1957)
  - Increased cover = Increased fire resistance
  - Increased cover = Increase in spalling
  - More spalling with continuity
  - Spalling at moisture content as low as 2.3%
- Spalling – cause & effect
  - Moisture content & permeability
  - Stress, Aggregate type, etc
  - Loss of section, exposed rebar
  - Flat slabs and columns most vulnerable

Changes in Modern Concretes

- Composition change
  - Early strength rates
- Permeability
  - Higher strength concrete
  - Lower permeability
- Structural configuration
  - PT Slabs
  - FE design

Table 5: Historical data on the ratio of 3 to 28 day strengths of concrete

Date	Ratio of 3 to 28 day strength
Postwar	0.406
1953	0.424
1957	0.441
1960	0.457
1965	0.459
1970	0.500
1975	0.500
1980	0.545
1985	0.554
1990	0.553
1992	0.554

Historical Research

- PT Slabs
  - Herberhen and Van Damme tests
  - Value of recent tests questionable (PT and Precast)
- Columns
  - 15% loss of area = 34% loss of strength
  - Modern concrete may be more susceptible

Table 1: Fire test data on continuous flat slabs

Slab no	inte spai	…	BS8110 min)
P1	(		60
P2	(		!0-180
P3	(		!0-180
P4	(		!0-180
P5	(		!0-180
P6	(		›240
P7	(		!0-180
P8	(		!0-180

NOTES:

Table 4: A comparison of the levels of spalling in various test series

Test series	No. of columns tested	No. with severe spalling	Percentage with severe spalling
National Building Studies 12	18	4	22
National Building Studies 18	31	4	13
Series C	12	7	58
Series D	20	18	90

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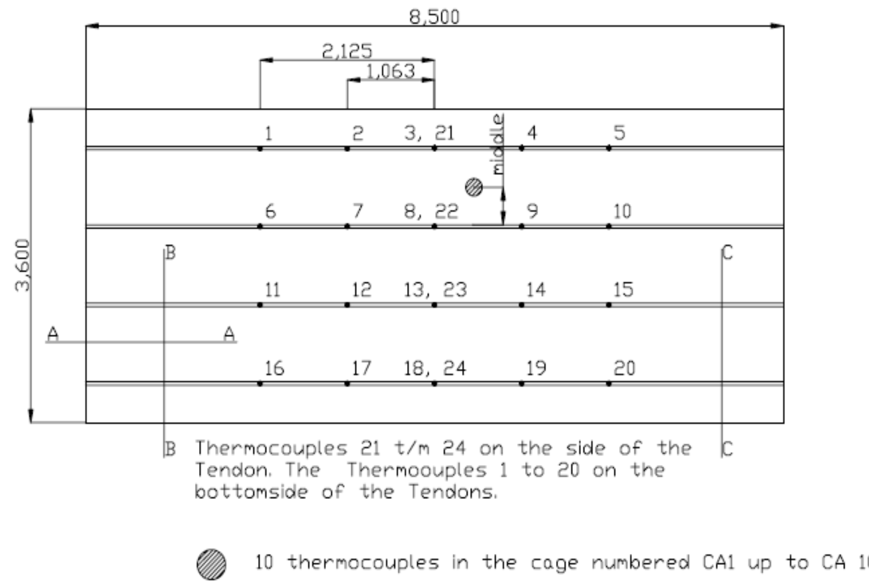
Post tensioned slab fire test

- Slab Configuration
  - – 8.5 x 3.6 m slab, 250 mm thick
  - – RC40 with OPC and Thames Valley Gravel, MC 4.6%
  - – Bonded tendons, 4 per duct, 40 cover
  - – 2 hour fire resistance
  - – 34 Type K thermocouples

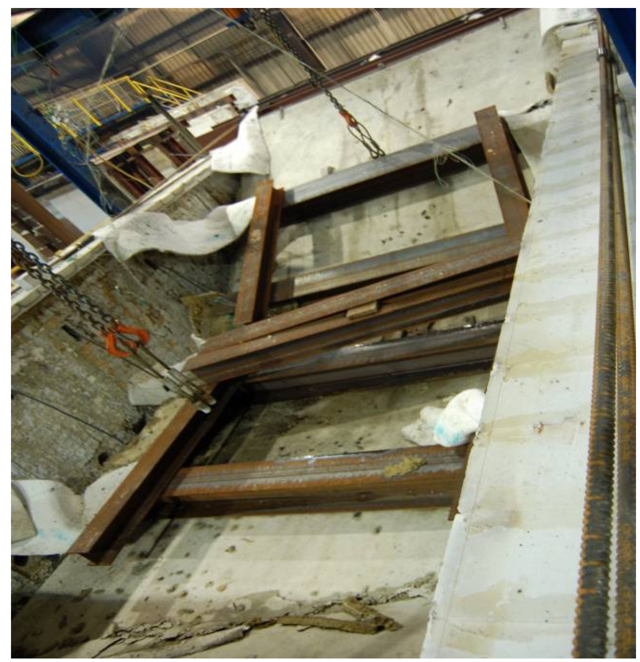


Post tensioned slab fire test

- Test Configuration
  - Standard fire test temperature curve
  - 20 type K thermocouples, plate (control) and wire
  - Restrained test, 1200 kN force, 10% preset
  - Twin hydraulic rams with spreader beams
  - Deflection via 3 LVDT gauges at mid-span
  - Load ratio of 0.5

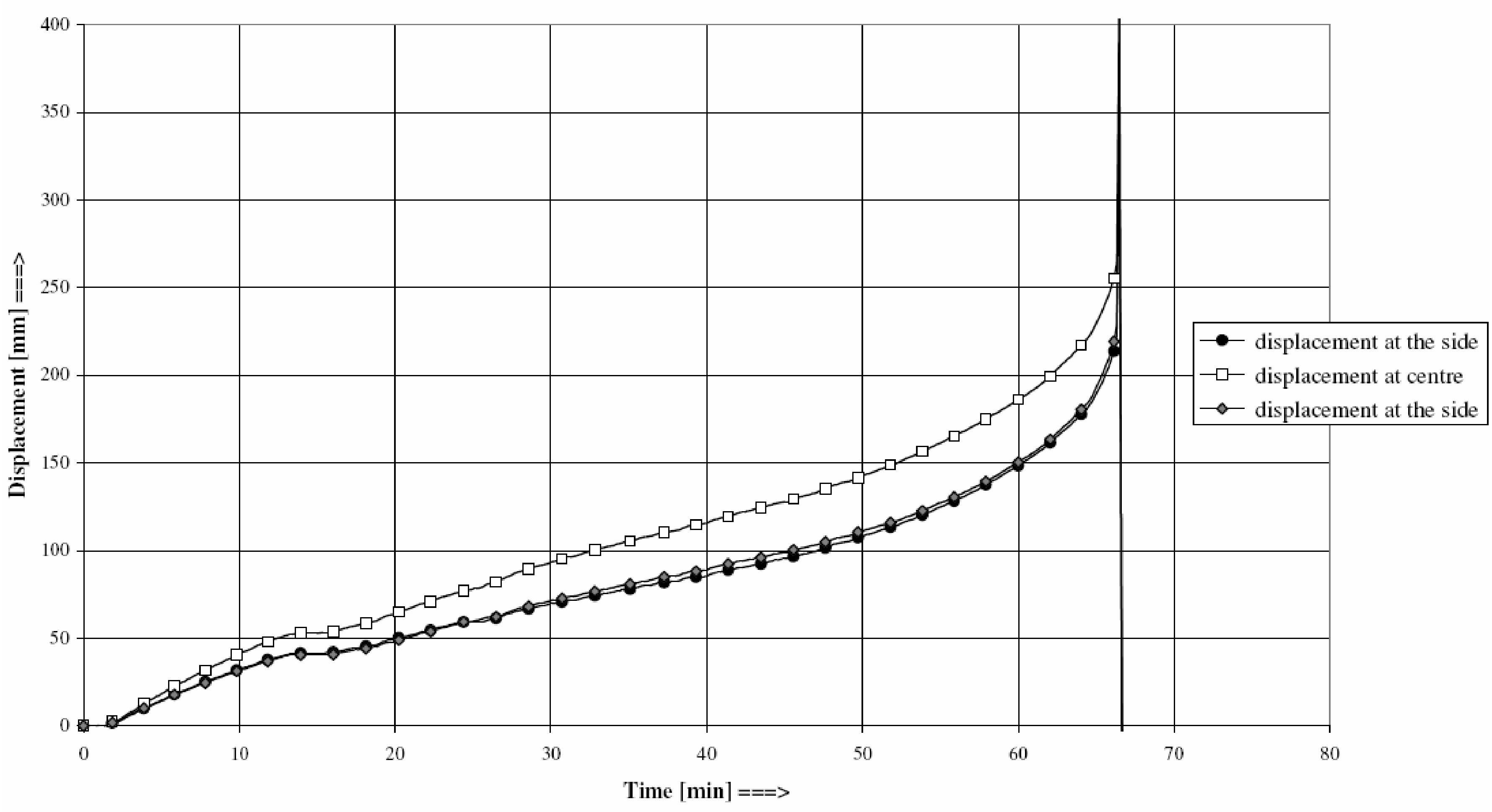
Test Results

- Summary
  - – 11 mins - Spalling began
  - – 18.5 mins - Max restraint force reached
  - – 20 mins - PT ducts visible
  - – 28 – Spalling reduces, steady increase in deflection
  - – 66 mins - Collapse



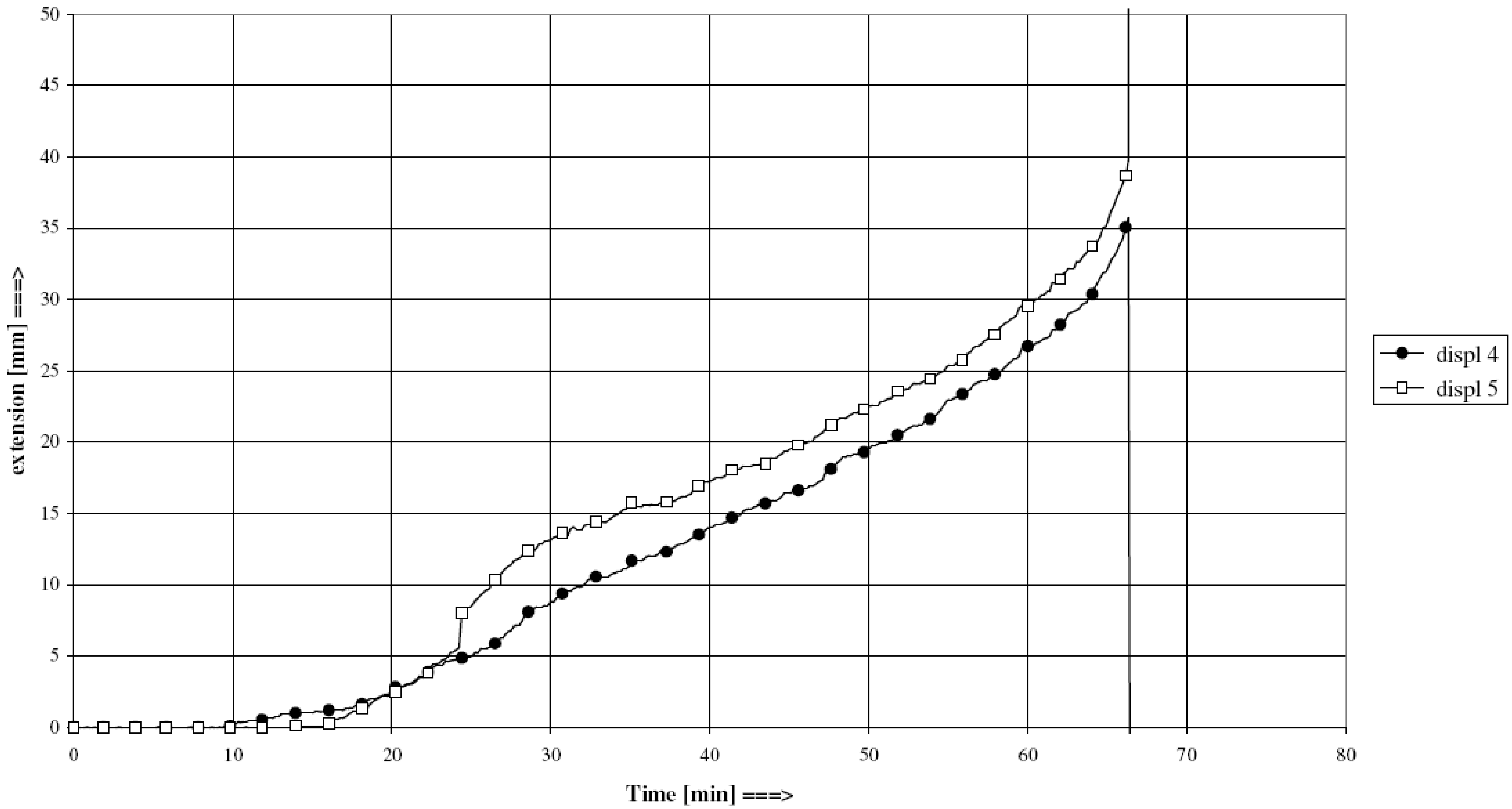
Test Results

- Vertical Deflection



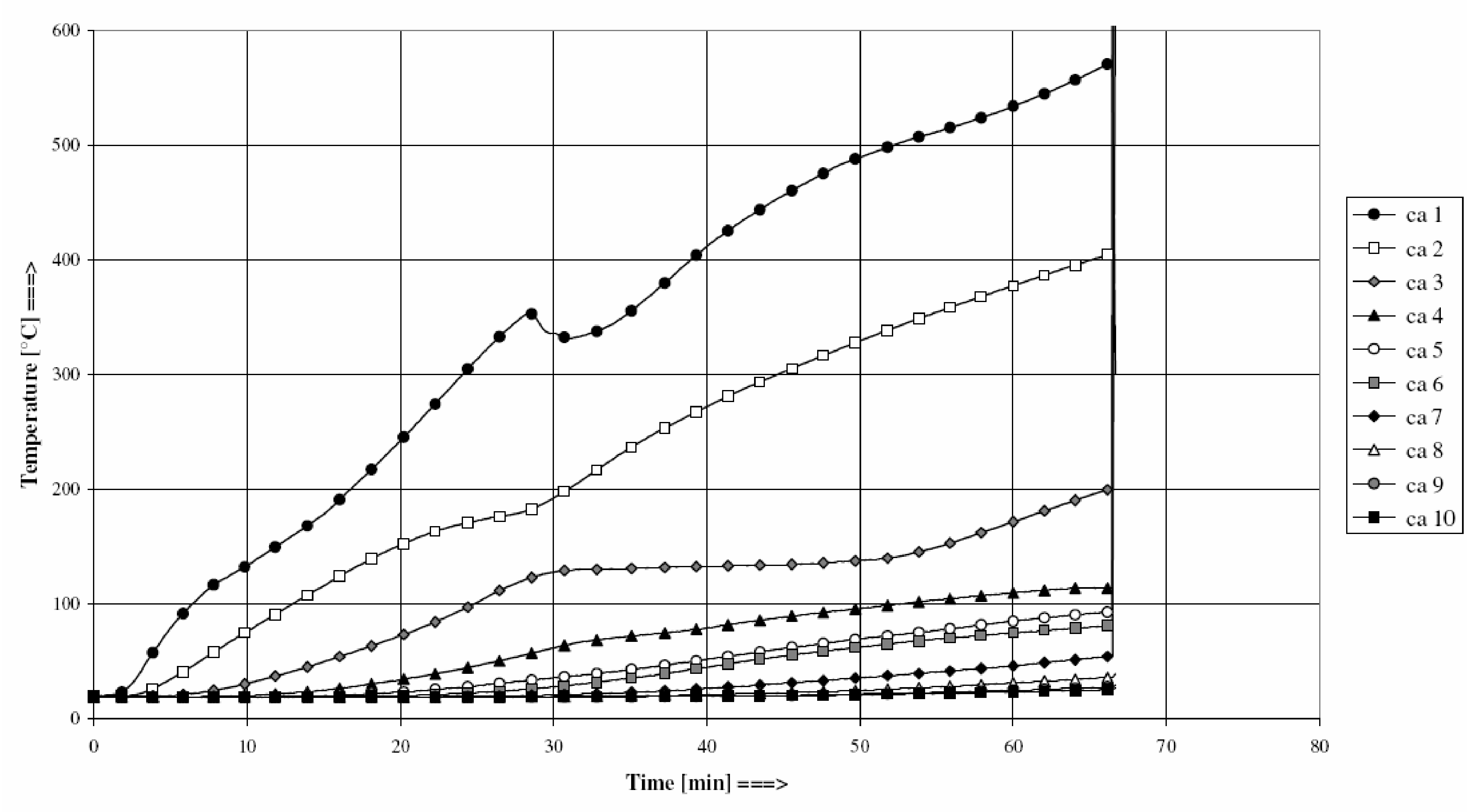
Test Results

- Expansion



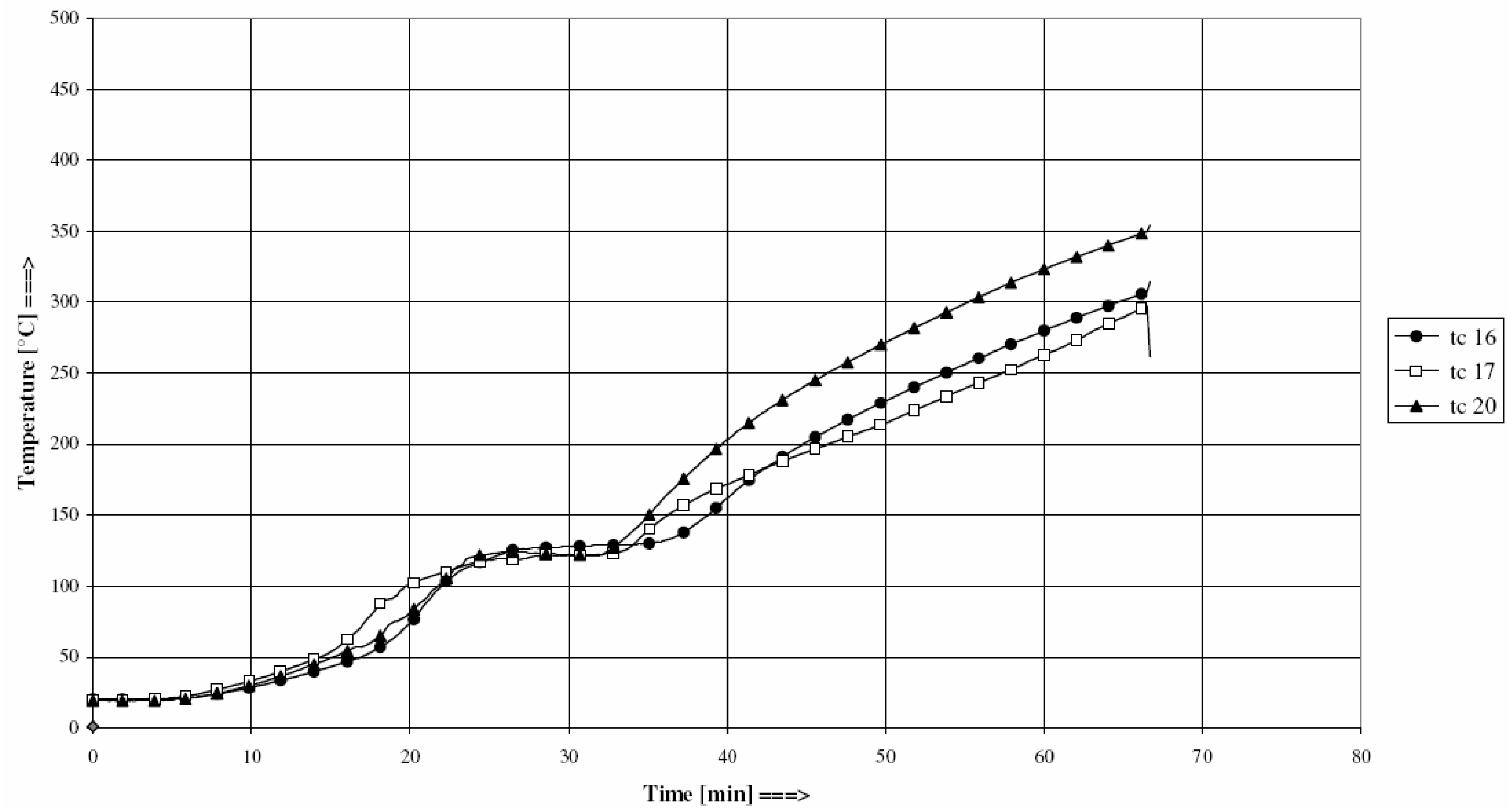
Test Results

- Temperature Profile in Slab



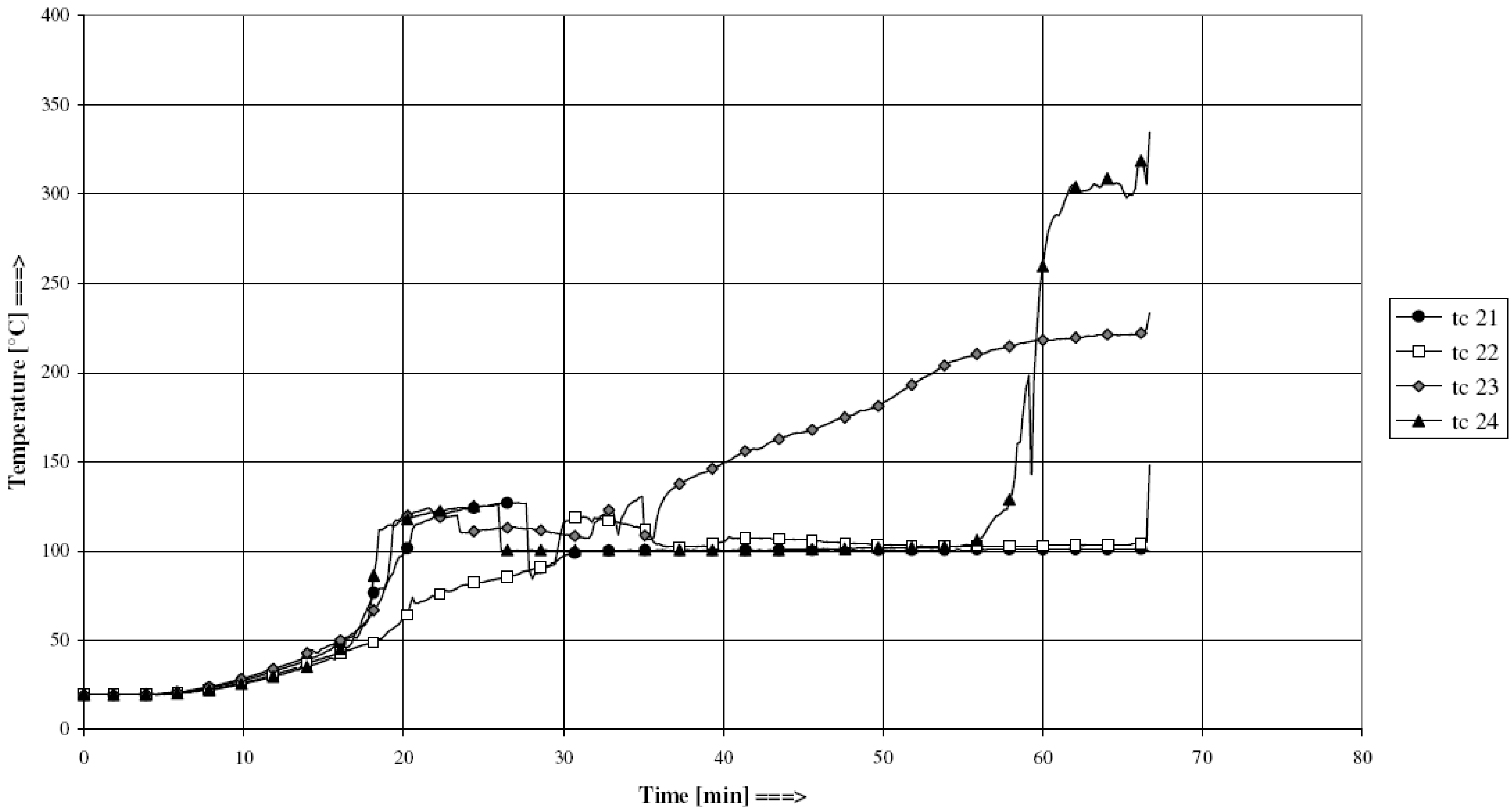
Test Results

- Temperature of PT Duct (Bottom)



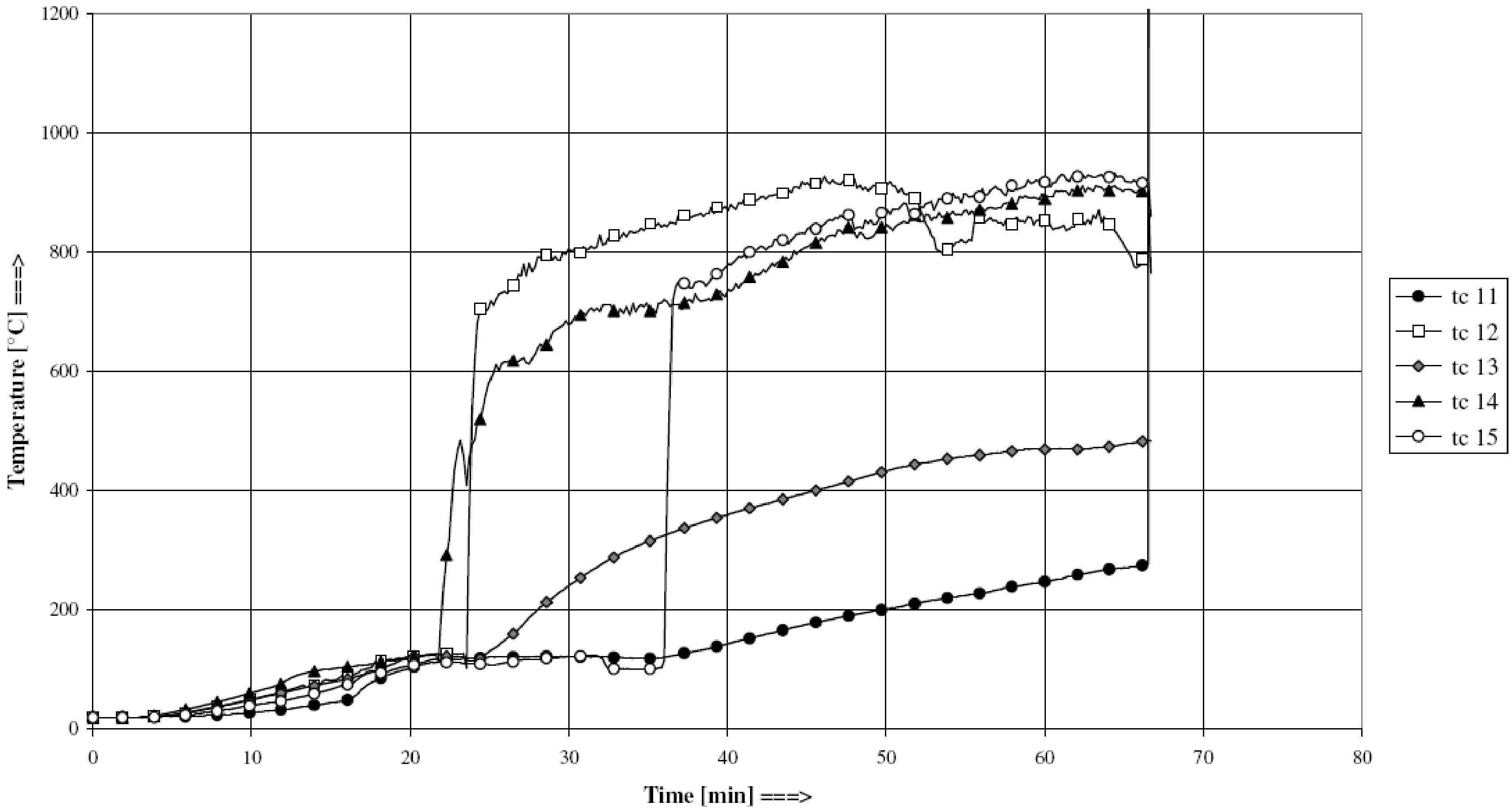
Test Results

- Temperature of PT Duct (Side)



Test Results

- Temperature of PT Duct (Spalled)



Overview

- PT Slab Overview
  - PT stress +2 N/mm^2
  - Restraint forces significant, ≥ 1.3 N/mm^2
  - PT ducts vulnerable to spalling
  - Concrete cover questionable in terms of duct temperature even with minor spalling
  - Additional btm mesh should be considered
  - Additional large scale tests
  - Information on long-term moisture content

Questions