INTERNATIONAL PRESTRESSED HOLLOWCORE ASSOCIATION

HOLCOFIRE

Behaviour of prestressed hollowcore floors exposed to fire

Database with 162 fire test results

Wim Jansze

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- Introduction
- Holcofire Database explained
- Failure types
  - Bending
  - Shear
  - Shear-bending interaction
  - Spalling
  - Horizontal cracking
  - Other failure types
- Conclusions

Objective of database study

- Not only perform new fire tests, but also learn from fire tests conducted in past
- Collect as many fire tests as possible ("Europe") and perform a meta-analysis
- Meta-analysis is defined as "*a systematic method of evaluating statistical data based on results of several independent studies on the same problem. A meta-analysis produces a stronger conclusion than can be provided by any individual study*."

Holcofire database study

- Technical paper published 18 June 2013

TECHNICAL PAPER

PROJECT HOLCOFIRE [1]

FIRE RESISTANCE OF HOLLOW CORE FLOORS

HOLCOFIRE DATABASE – META-ANALYSIS ON 162 FIRE TEST RESULTS EXECUTED BETWEEN 1966-2010[2]

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Abstract. Since the 1960s many fire tests have been conducted on prestressed hollow cores slabs and floors in fire testing laboratories in order to evaluate the application of hollow cores under fire conditions. The tests not always behaved as wished and the behaviour could not always be explained fully, let alone, recalculated. This paper deals with the meta-analysis of the fire tests that have been gathered in the so called Holcofire database. The Holcofire database consists of 162 independent European fire test results covering a period of 45 years from 1966 to 2010. Content analysis of the database shows that in 91 fire tests a failure did not occur when the test was stopped, while in 71 fire test a failure was observed, either premature or intended. The main failure types observed under fire conditions in the database are bending failure exhibited by exceeding rate of deflection (11x); shear and anchorage failure (42x); shear-bending interaction failure (6x); explosive spalling (5x); horizontal cracking (4x), and other uncommon failure types (3x). A thorough meta-analysis on the 162 independent fire test results shows that nowadays 94,5% of the database fire test results can be explained with the design models and requirements stated in the available European standards (EN1992-1-2, EN1168, EN1363-1, EN1363-2). Statistical analysis in combination with the method of maximum likelihood were used to state the accuracy of the design model for the bending capacity of a hollow core cross section, the design model for anchorage and shear capacity for single slabs and floor systems, and for the shear-bending interaction capacity. 5,5% of the fire test results in the database, mainly related to explosive spalling and horizontal cracking, cannot be explained fully today. The phenomena are not yet fully understood, although it becomes clear from the fire tests that moisture content, thick topping, and floor restraints are important influencing parameters. Therefore, explosive spalling and horizontal cracking remain subjects for further research in the Holcofire project in the year 2013.

[1] HOLCOFIRE is a European research project executed under BIBM Product Group "Hollow Core."

[2] The background reports of this paper were reviewed by Prof.ir. A.C.W.M. Vrouwenvelder and Prof.dr.ir. J.C. Walraven, Delft, The Netherlands. The integral review text of the background reports is published in Appendix D of this technical paper

Rough overview of database

162 single analyzable fire tests have been collected executed between 1966 and 2010 (45 years):

- Finnish studies performed by VTT PAL between 1971 and 1991;
- Belgium studies by CBR, FEBE and RUG between 1971 and 1999;
- French CTICM and Swiss ETH/EMPA studies on slim floor structures between 1992 and 1996;
- IBS studies between 1983 and 1996 in Germany;
- Dutch TNO studies between 1999 and 2001;
- Danish studies by DIFT, SPTRI and BRE between 1999 and 2005;
- Eastern European studies (ITB, ZAG, CVUT) between 2001 and 2008;
- Building structure study in UK in 2007
- Peikko tests in 2009 on steel beams
- Dutch Efectis tests on Rotterdam fire in 2010

Fire tests on hollow cores

Fig 1. VTT-PAL 2892-71 [1971]

Fig 2. RUG 9157 [1999]

Fig 3. TNO R-HVP260S11 [2001]

Fire tests on hollow cores

Fig 4. SPTRI P502015 [2005]

Fig 5. SPTRI Peikko [2009]

Fig 6. BRE test 1 [2007]

Fig 7. EFNL S-A400—T50 [2010]

20 fire test laboratories

Table I – Overview of fire test laboratories

BRE	Building Research Establishment	Middlesborough	United Kingdom
CBR	CBR Ergon laboratory	Lier	Belgium
CSI	CSI Gruppo IMQ	Milan	Italy
CTICM	Centre Technique Industriel de la Construction Metallique	Mezieres-les-Metz	France
CVUT	Technical University in Prague	Mokrsko	Czech republic
DIFT	Danish Institute for Fire Technology	Hvidovre	Denmark
EFNL	Efectis Nederland	Delft	Netherlands
FROSI	Fire Research Organisation Special Investigation	Unknown	United Kingdom
IBS	Institut für Brandschutztechnik und Sicherheitsforschung	Linz	Austria
IG	Instituto Giordano - Laboratorio di Recherche di fisica tecnica	Bellaria	Italy
ITB	Building Research Laboratory	Katowice	Poland
EMPA	Eidg. Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe (ETH Zurich)	Dubendorf	Switserland
SPTRI	SP Technical Research Institute of Sweden	Borås	Sweden
RIFS	Ministry for Emergency Situations	Minsk	Belarus
RUG	Rijksuniversiteit Gent	Gent	Belgium
TNO	Toegepast natuurwetenschappelijk onderzoek	Delft	Netherlands
TUB	Technische Universitat Braunschweig	Braunschweig	Germany
UP	University of Perugia		Italy
VTT PAL	Valtion Teknillinen Tutkimuskeskus - Palotekniikan laboratorio	Helsinki	Finland
ZAG	ZAG fire laboratory	Ljubljana	Slovenia

*) TNO and EFNL is the same laboratory, but tests were conducted under different ownership

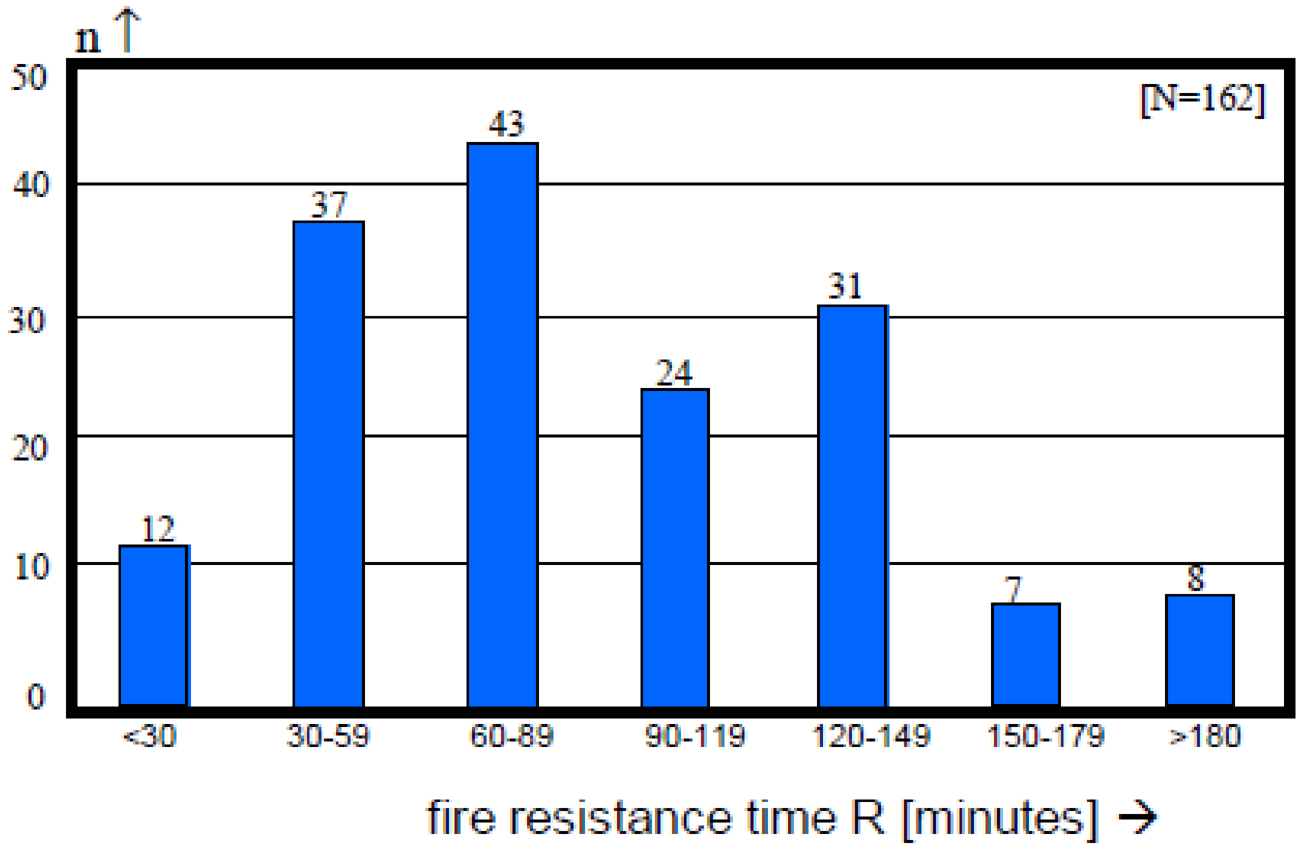
Database in MS Word reporting style

Fire resistance of hollow core floors
Holcofire Database – Meta-analysis on 162 fire test results executed 1966-2010

Holcofire fire test #	Fire test name	test year	Fire curve	Slab depth [mm]	top ping [mm]	slab width [mm]	total web width [mm]	Total area of strand [mm2/slab]	Axis distance	length of test set up, [m]	width of test set-up [m]	no of slabs	test set-up	EN13 65-2	time [min]	Failure after fire
H26	CBR 78/85 SPG 27/6 (protected)	1978	ISO 834	265	0	1,2	233	312	40	1,8	1	1	HCS	0	173	R-NO
H27	VTT PAL 9498	1979	ISO 834	150	0	1200	231	208	35	6	2,4	2	SYS	1	50	R-NO
H28	VTT PAL 0795	1980	ISO 834	290	0	1200	260	372	80	6	2,4	2	SYS	1	190	DF
H29	RUG 3681	1980	ISO 834	152	30	595	175	248	39	6	1,8	3	FLR	0	76	R-DF
H30	RUG 3682	1980	ISO 834	200	30	595	266	118	33	6	1,8	3	FLR	0	126	R-DF
H31	VTT PAL 1146b	1980	ISO 834	265	0				45	6	2,4	2	SYS	1	88	R-NO
H32	VTT PAL 1191	1980	ISO 834	265	0			0	45	6	2,4	2	SYS	1	112	R-NO
H33	VTT PAL 1350	1980	ISO 834	265	0			0	45	6	2,4	2	SYS	1	78	R-NO
H34	VTT PAL 1038a	1980	ISO 834	265	0	1200	232	279	55	6	2,4	2	SYS	1	105	R-DF
H35	VTT PAL 1038b	1980	ISO 834	150	0	1200	231	208	33	6	2,4	2	SYS	1	45	R-NO
H36	VTT PAL 1038c (protected)	1980	ISO 834	150	0	1200	231	208	33	6	2,4	2	SYS	1	262	R-NO
H37	VTT PAL 1275a	1980	ISO 834	265	0	1200	232	279	65	6	2,4	2	SYS	1	105,5	R-NO
H38	VTT PAL 2358	1982	ISO 834	150	0	1200	208	364	38	5,9	2,4	2	SYS	1	64	R-DF
H39	VTT PAL 2480	1982	ISO 834	275	0	1200	243	558	65	4	2,4	2	SYS	1	63	SA
H40	VTT PAL 2481	1982	ISO 834	215	0	1200	241	651	38	5,9	2,4	2	SYS	1	78	R-NO
H41	RUG 4514	1982	ISO 834	265	50	1200	287	520	61	5,45	1,2	1	HCS	0	150	R-NO
H42	TUB IBMB 82 1424/I-IV	1982	ISO 834	140	0	497	204	174	35	4,75	2	4	SYS	1	47	R-DF
H43	TUB IBMB 82 1424/V-VI	1982	ISO 834	160	0	497	254	145	35	4,75	2	4	SYS	1	95	R-NO
H44	IBS 2311	1983	ISO 834	160	0	1200	462	520	35	4,1	2	2	SYS	1	90	R-NO
H45	VTT PAL 4248	1984	ISO 834	265	0	2400	465	744	64	5,185	2,4	1	SYS	1	49	SA
H46	VTT PAL 4337	1984	ISO 834	265	0	1200	233	312	33	5,185	2,4	2	SYS	1	62	R-NO
H47	VTT PAL 4448	1984	ISO 834	160	0	1200	276	208	37	5,185	2,4	2	SYS	1	36	DF
H48	VTT PAL 4450	1984	ISO 834	265	0	1200	233	312	61	5,185	2,4	2	SYS	1	130	SA
H49	VTT PAL 4451	1984	ISO 834	275	0	1200	227	372	91	5,185	2,4	2	SYS	1	30	DF
H50	VTT PAL 4452	1984	ISO 834	265	0	1200	225	930	33	5,185	2,4	2	SYS	1	135	R-NO

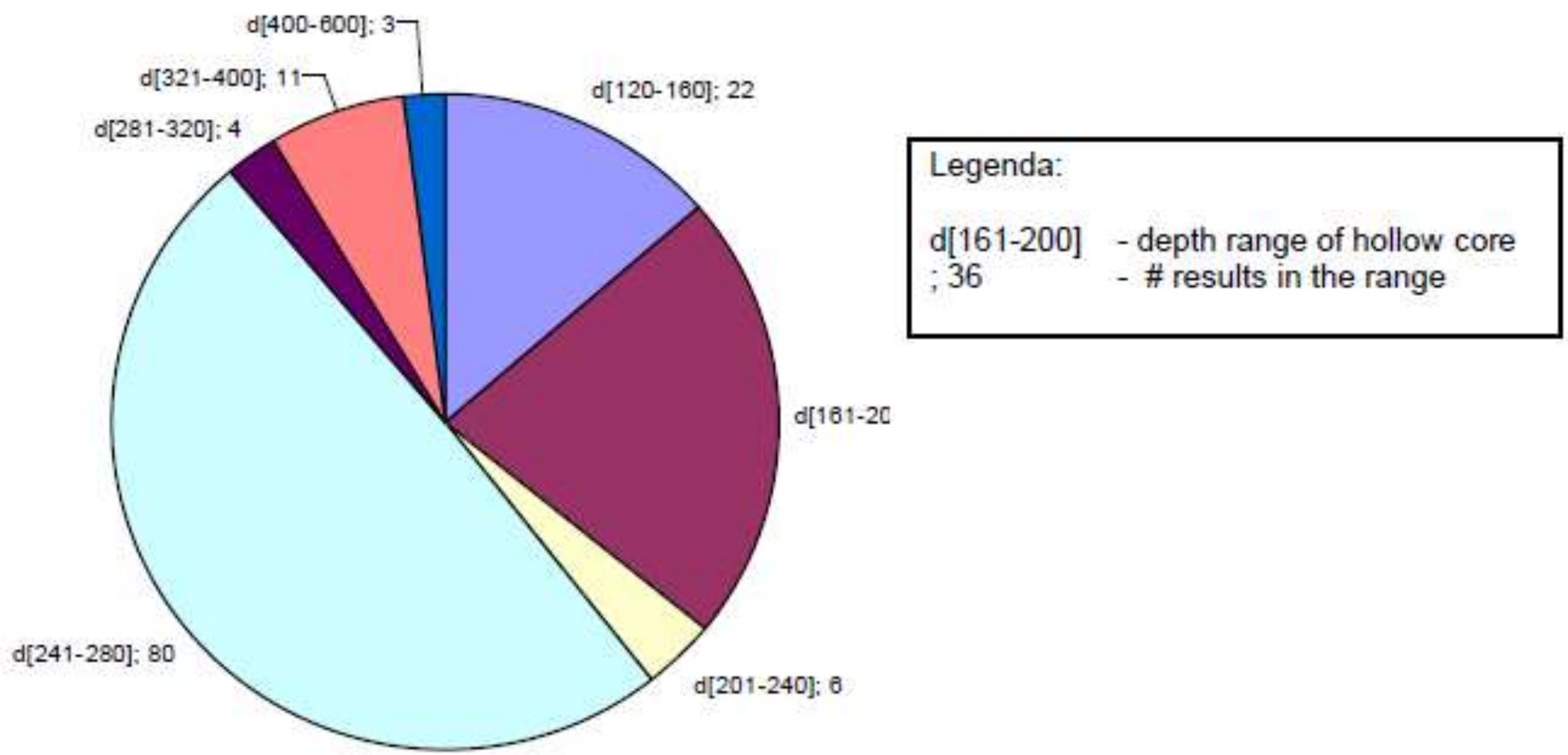
Some database figures

- Fire resistance time reached in fire tests (N=162)



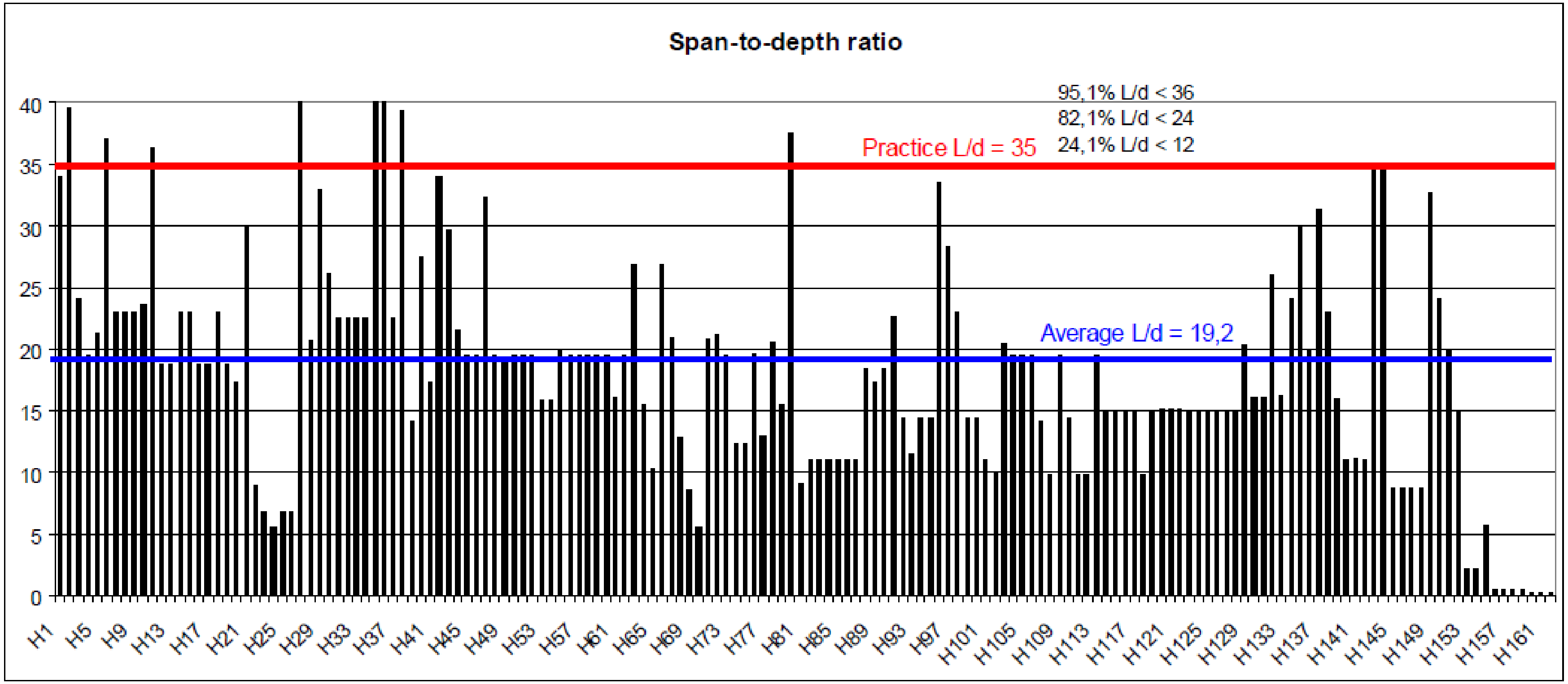
Some database figures

- Depths [mm] of hollow cores used in fire tests (N=162)



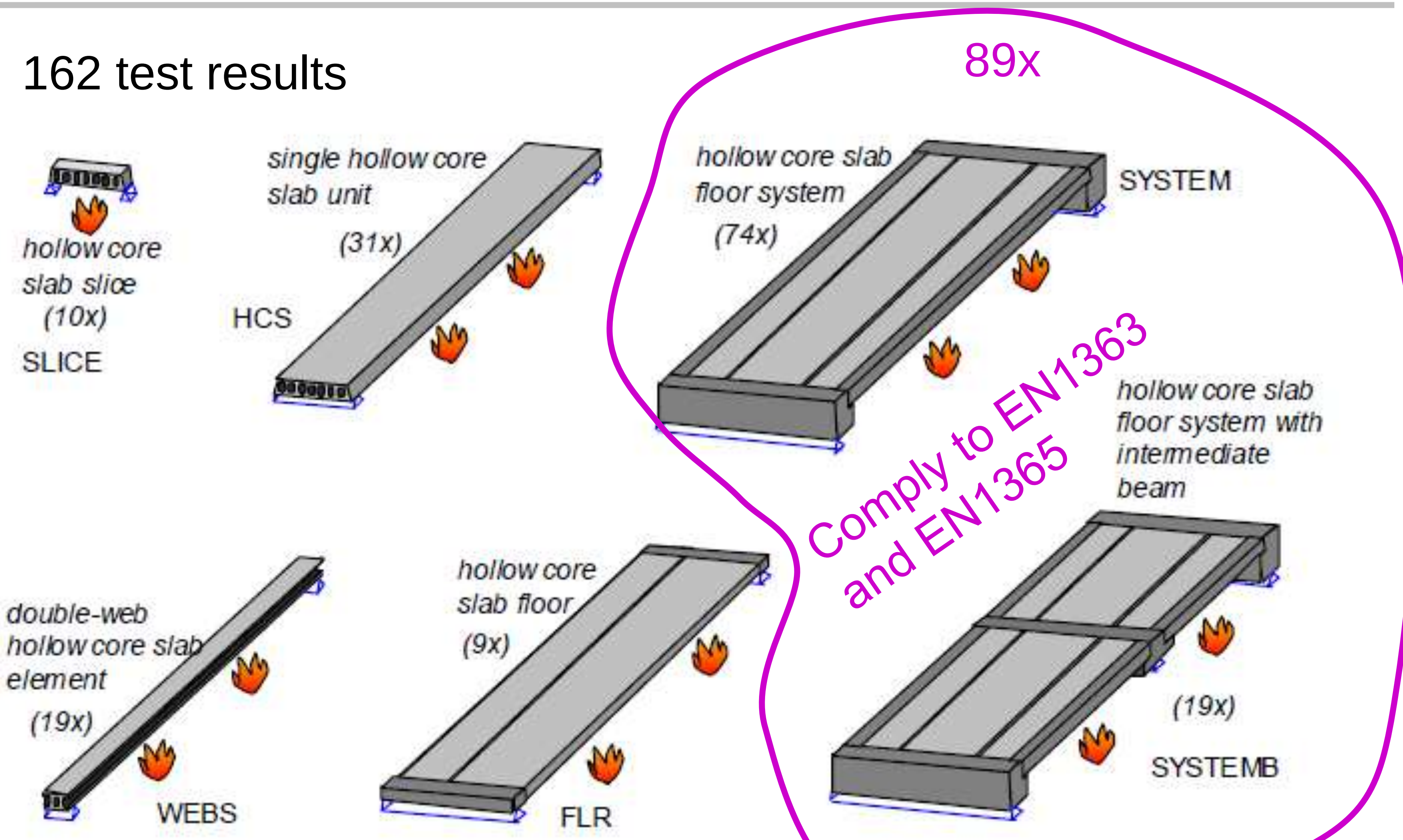
Some database figures

- The ideal span-to-depth ratio in practice is 35
- The average span-to-depth ratio in fire tests is 19,2
- Furnaces available 4m x 6m

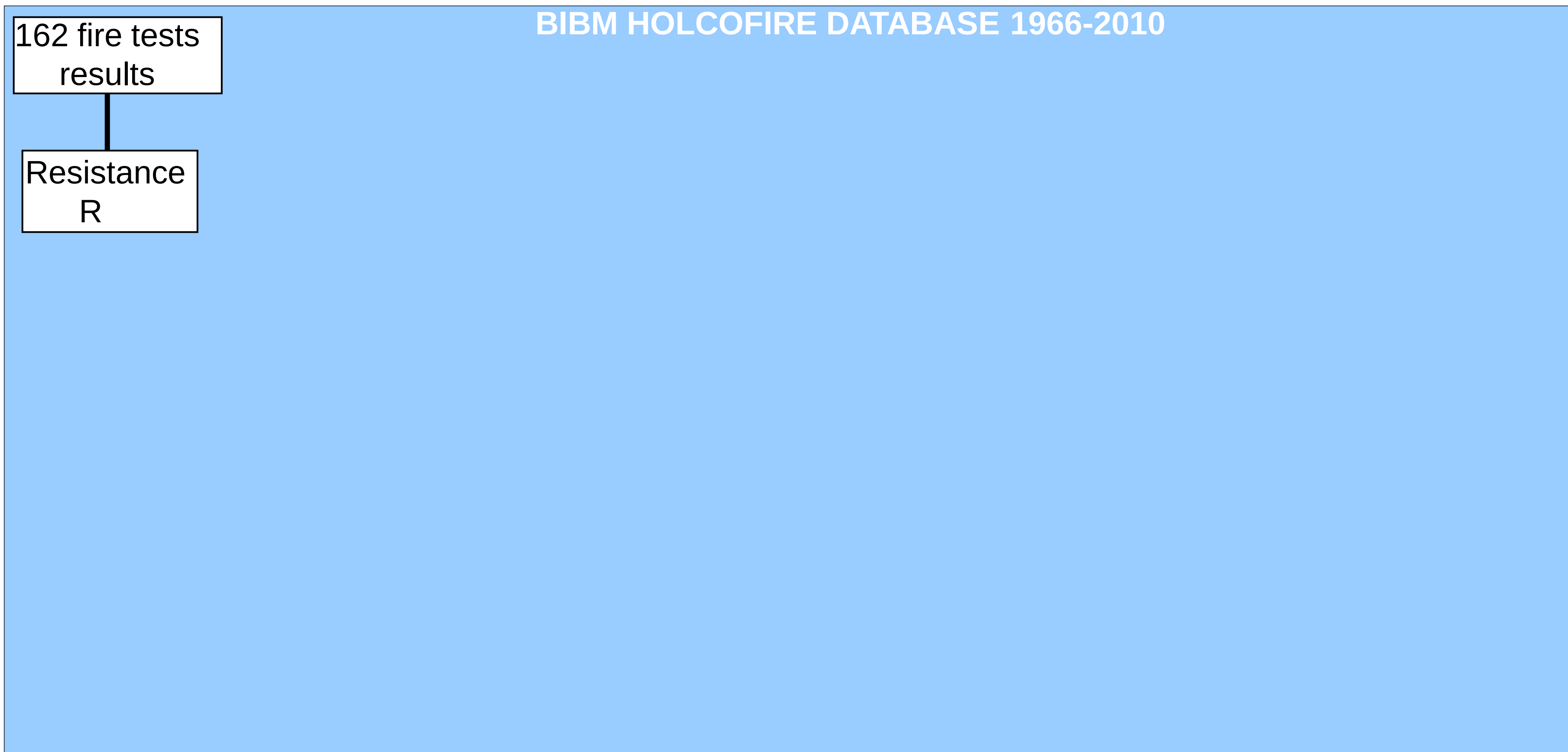


Geometry of test set-ups

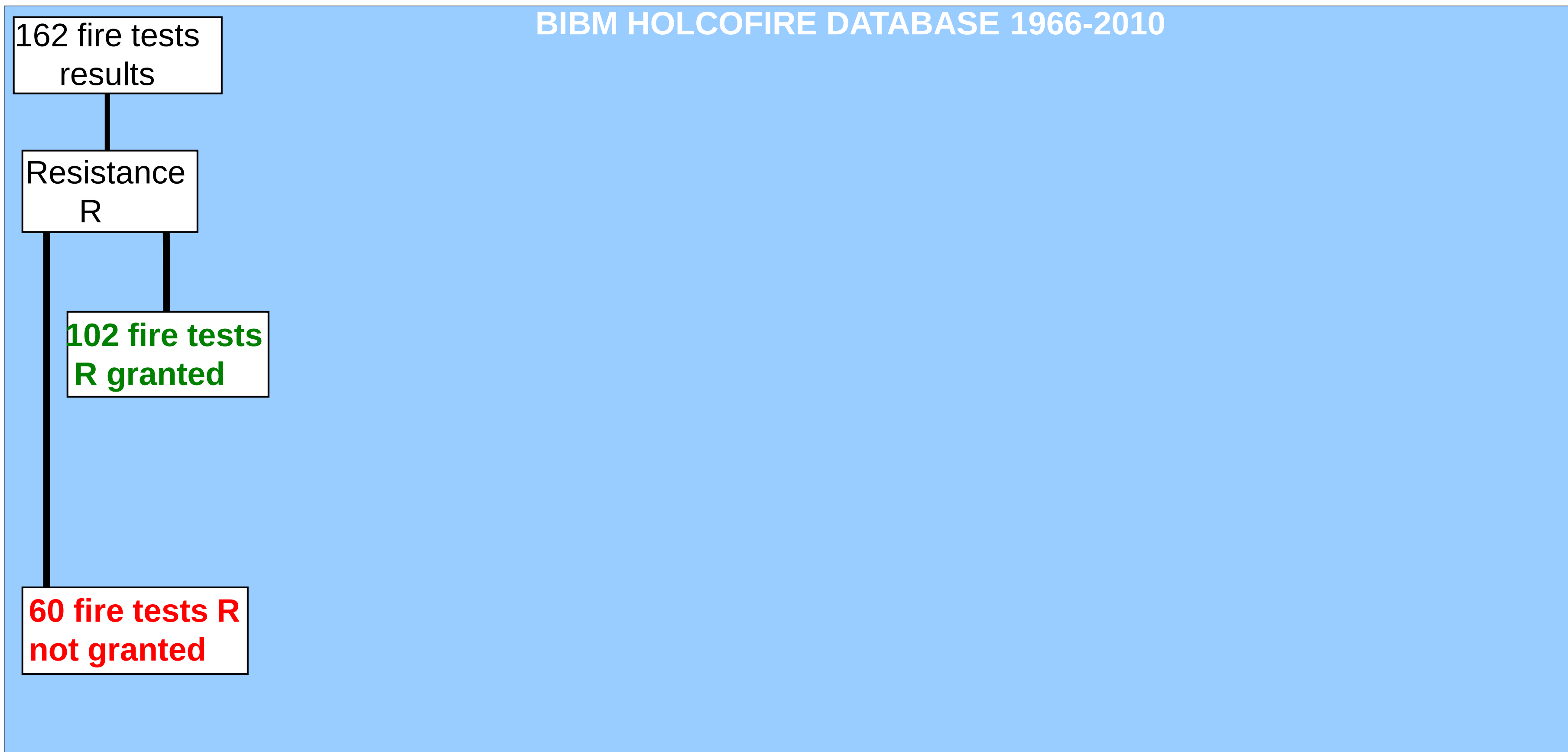
162 test results



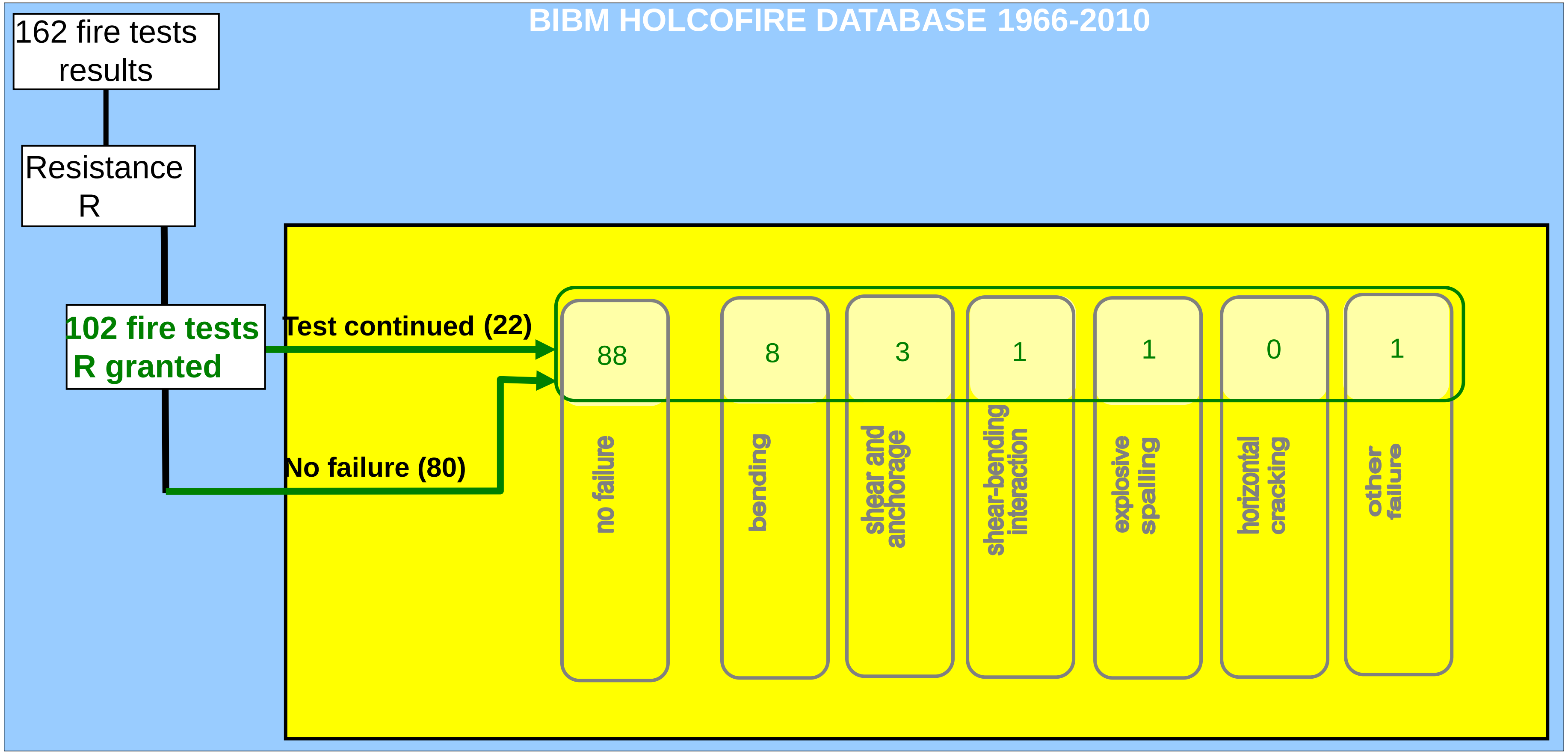
Holcofire database explained



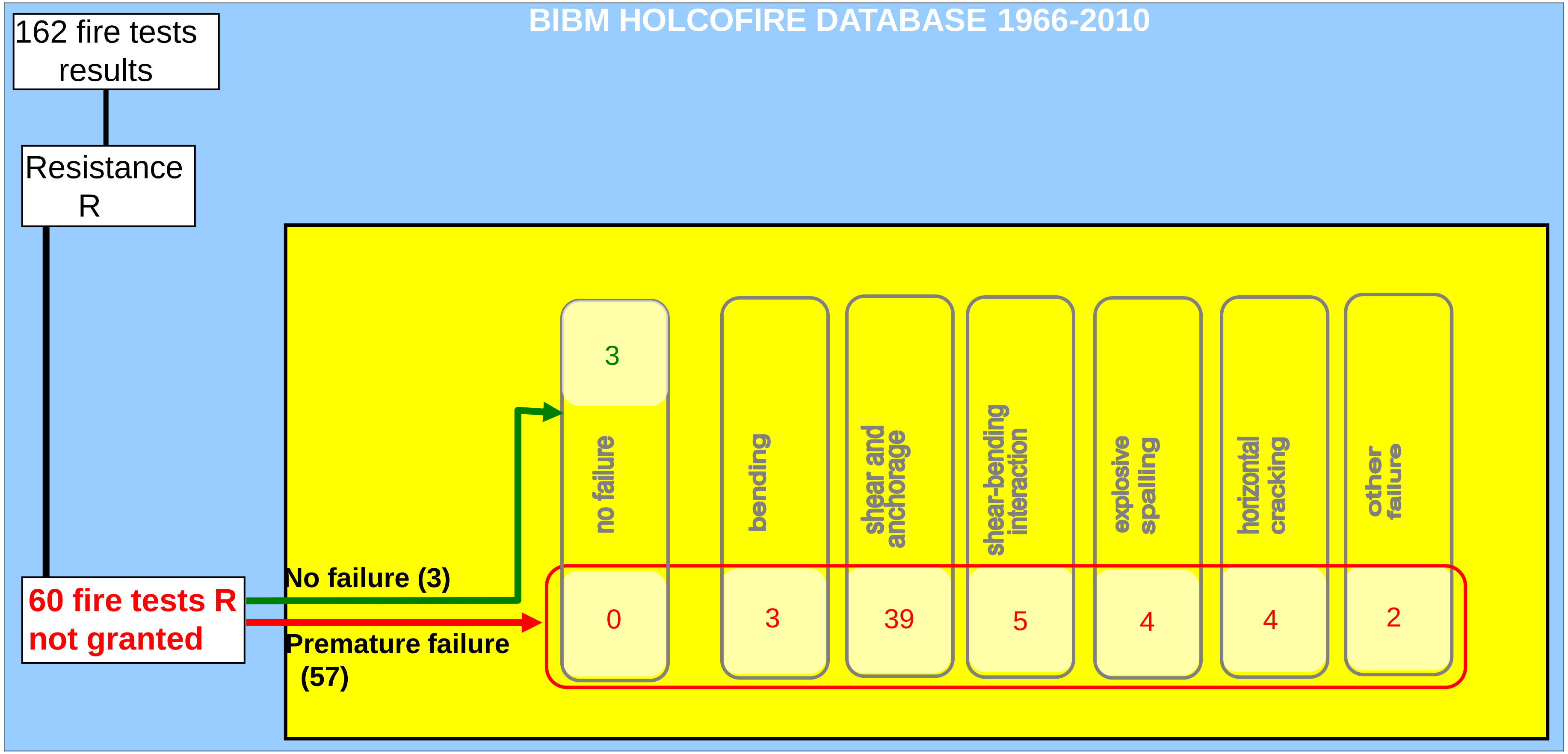
Holcofire database explained



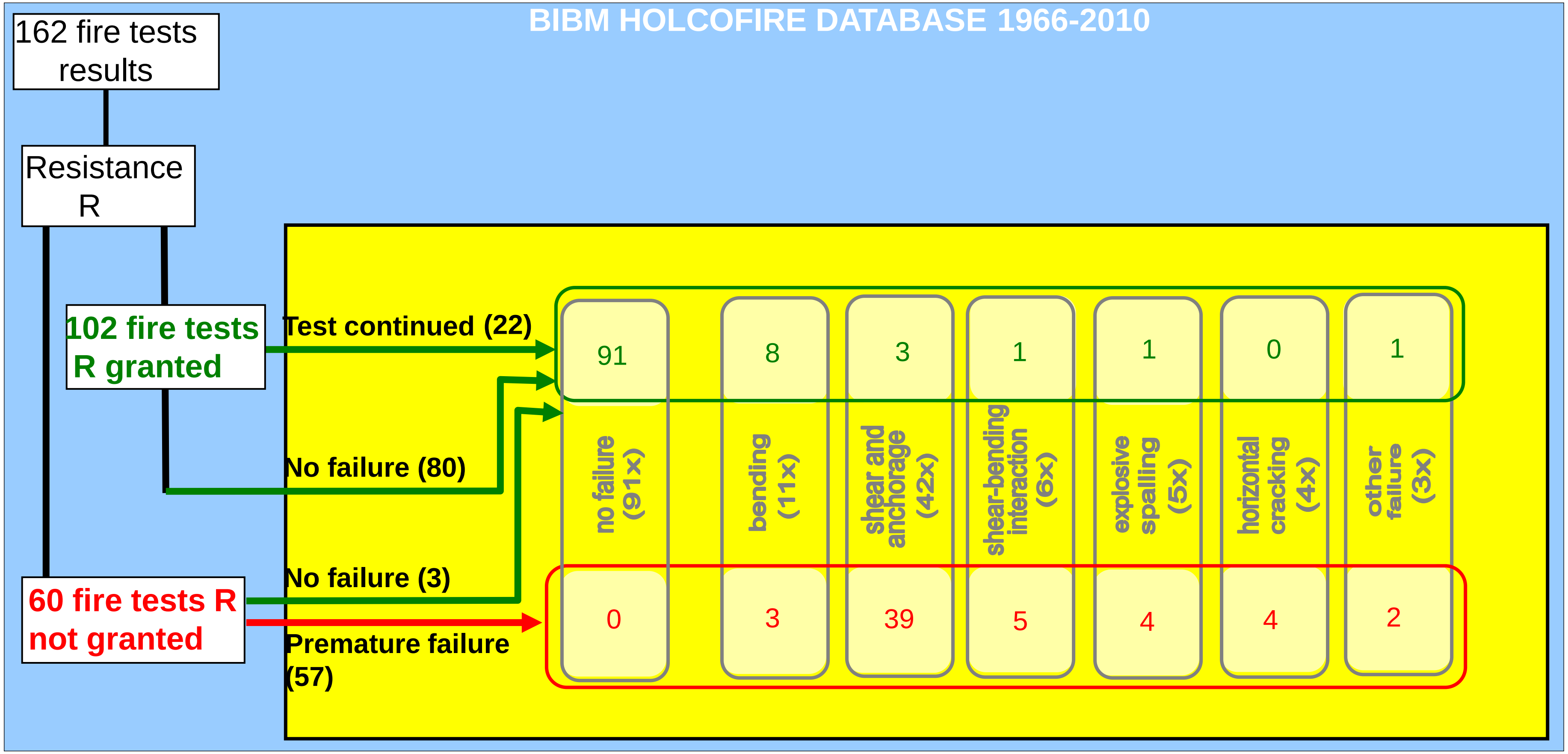
Holcofire database explained



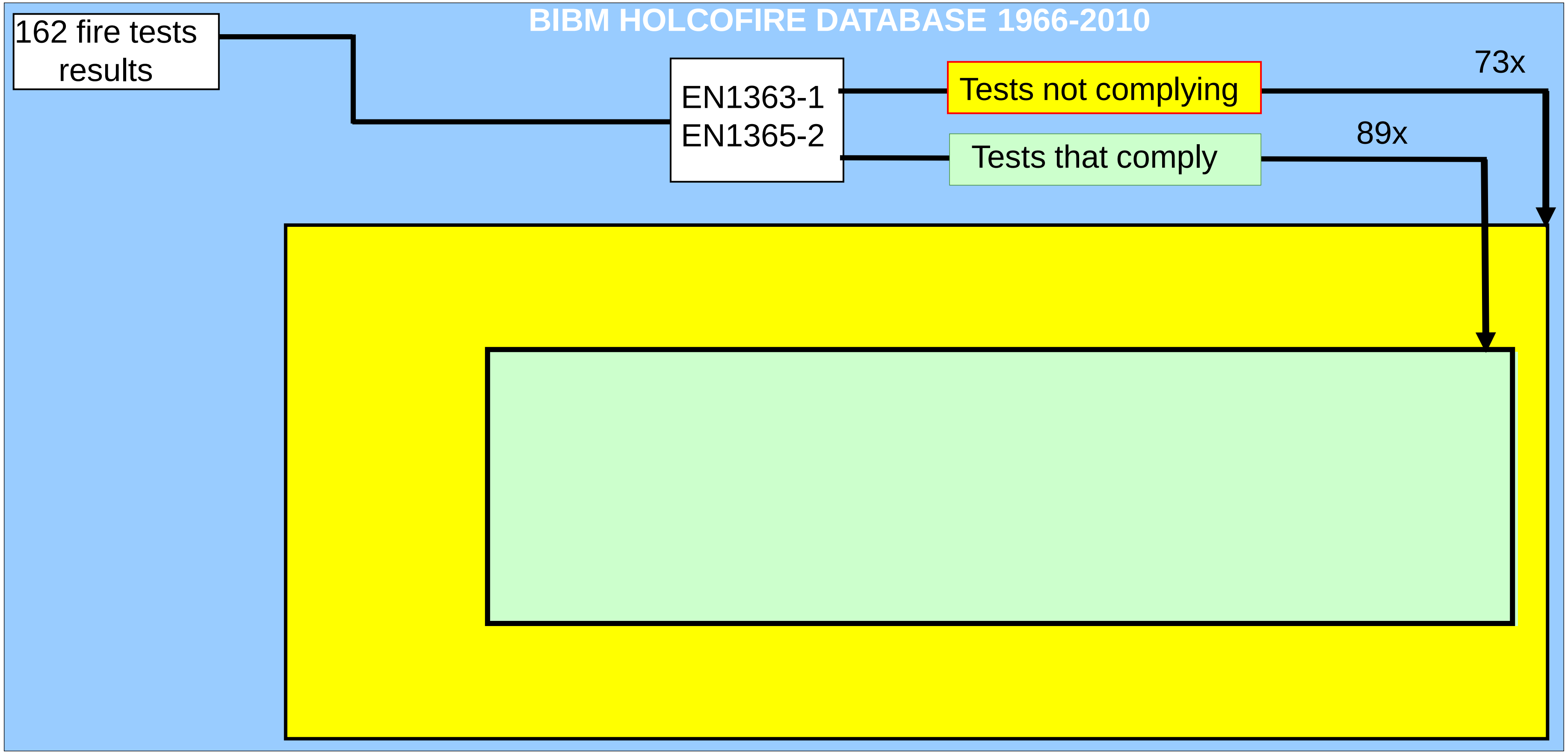
Holcofire database explained



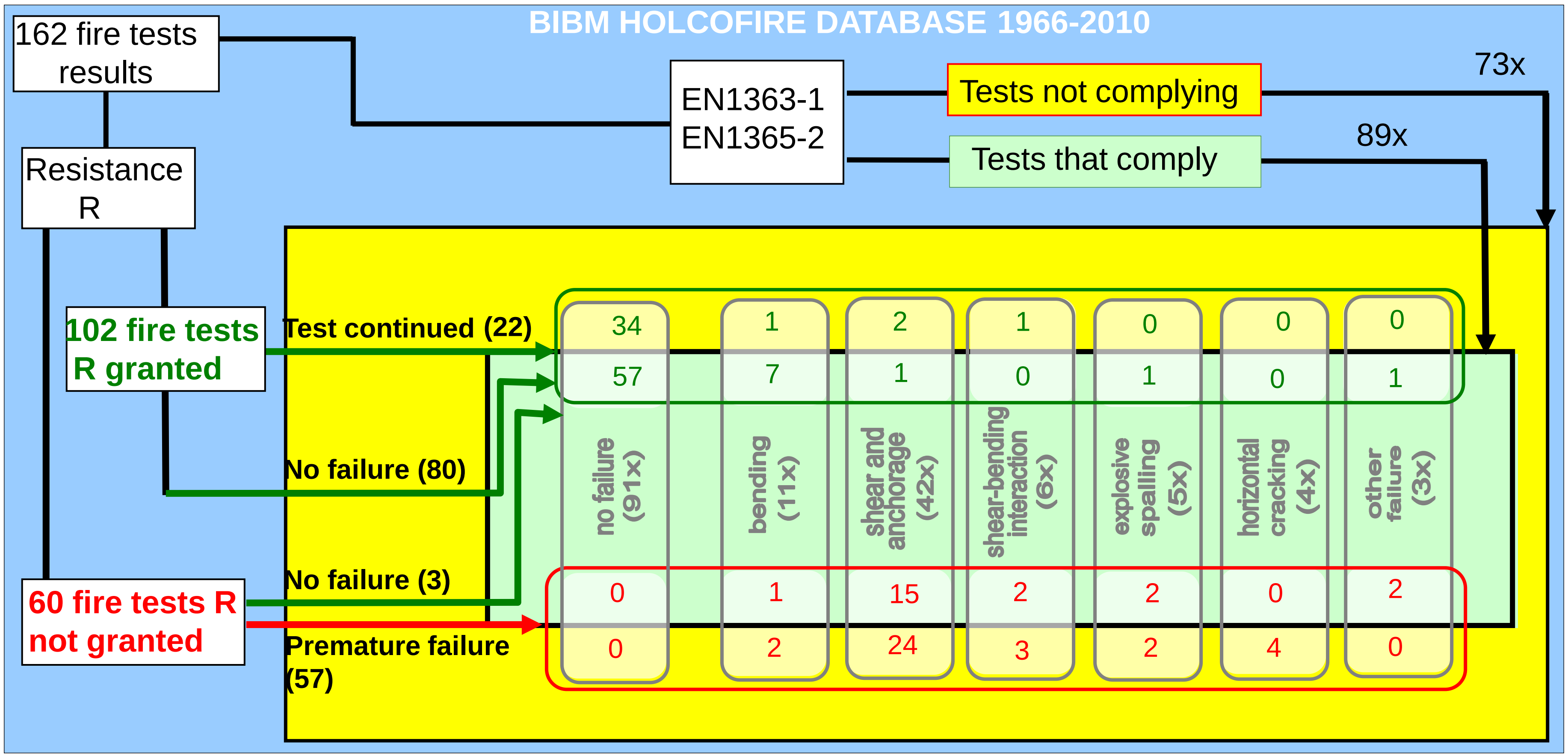
Holcofire database explained



Holcofire database explained

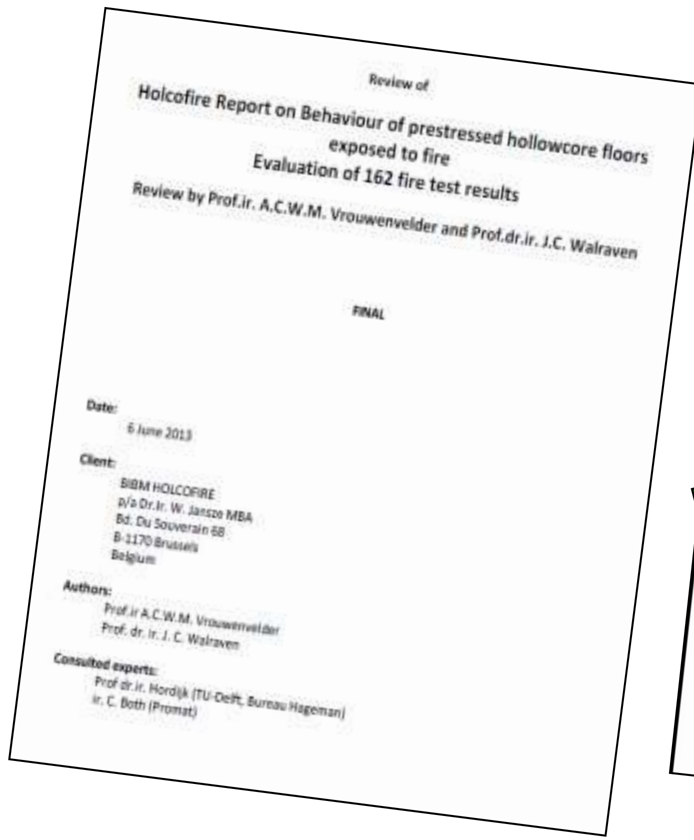


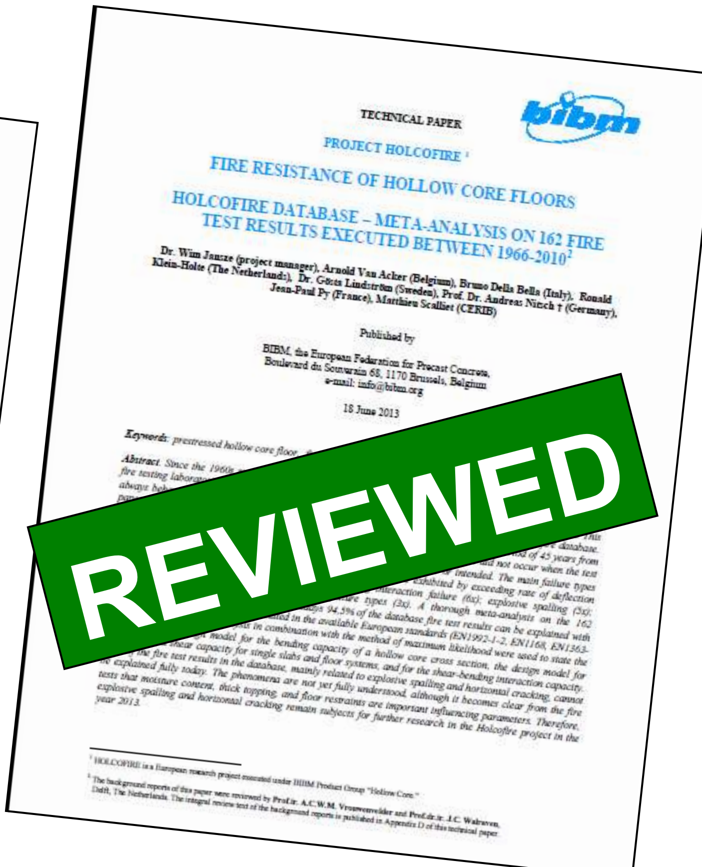
Holcofire database



Evaluation of database

- Database study is reviewed in February-May 2013 by Prof. Ton Vrouwenvelder and Prof. Joost Walraven, The Netherlands





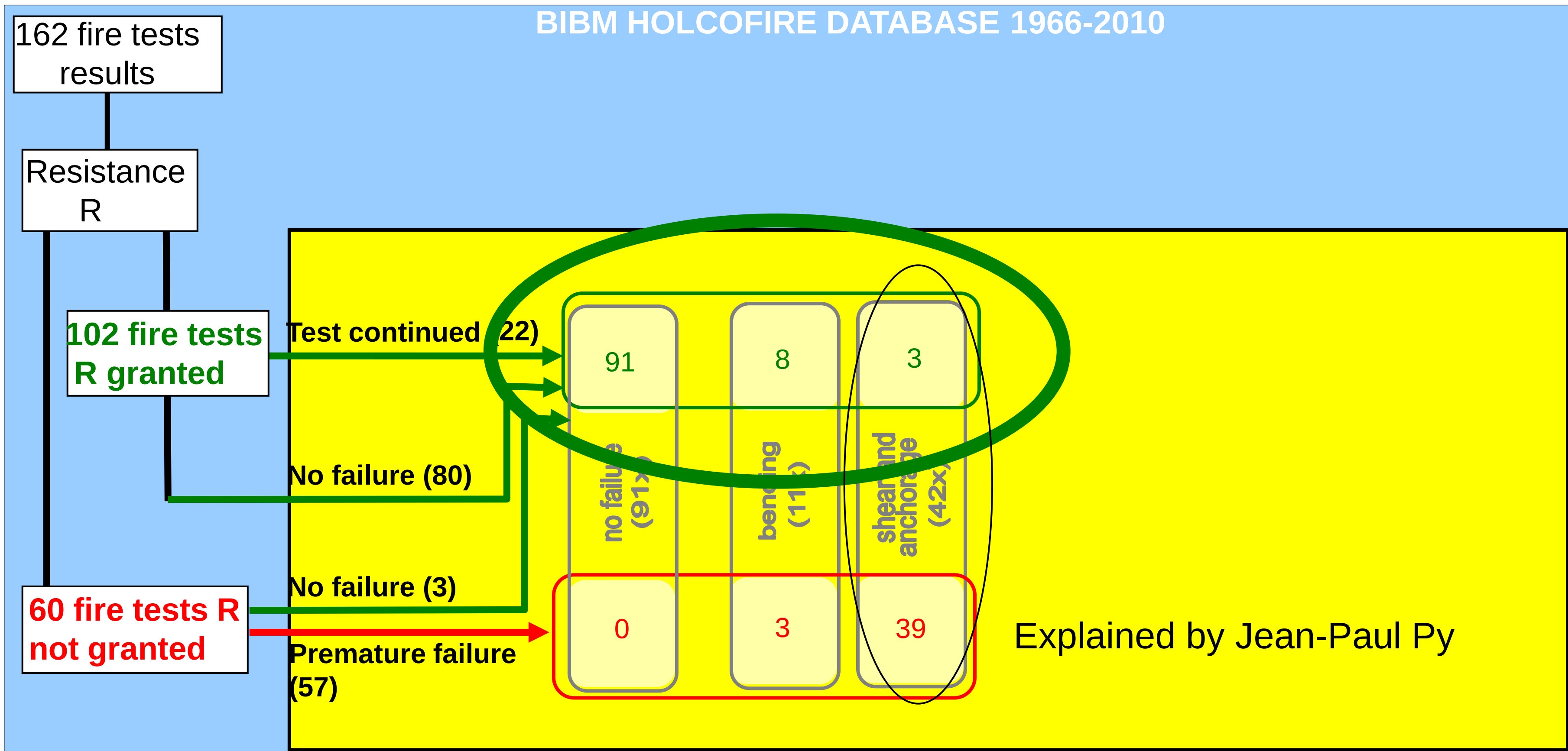
Reviewers

- “The reviewers would like to emphasize that they consider the work done to be a very good initiative and a valuable contribution to the assessment of structural safety of floors assembled with hollow-core slabs subjected to fire”.
- “The large number of tests from various origins, with a large spectrum of parameter variations, have been classified with regard to their failure mode and have been analyzed appropriately”.

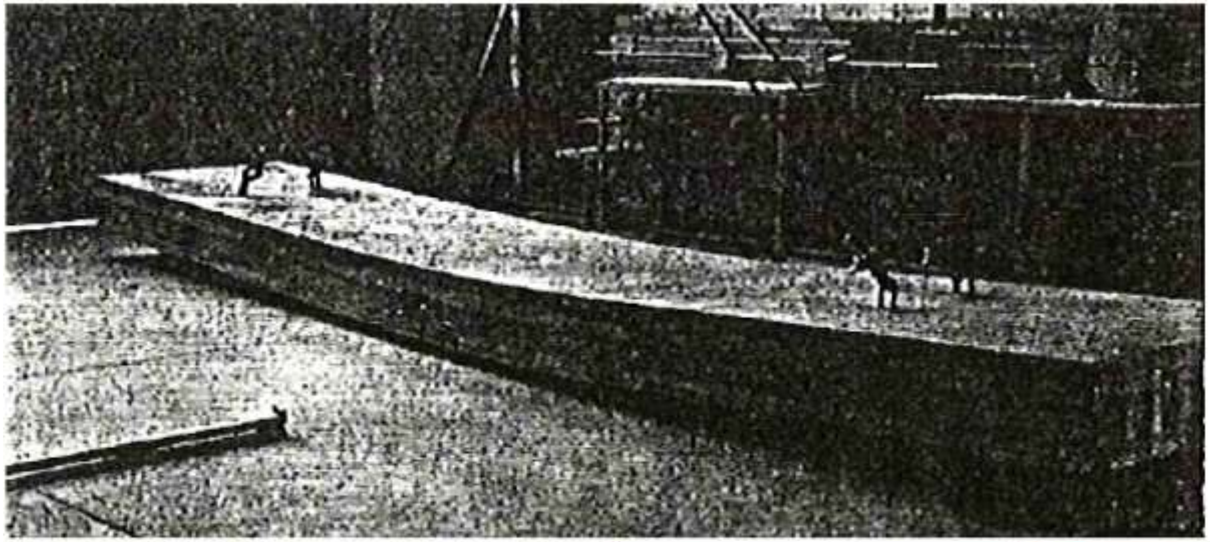
Reviewers

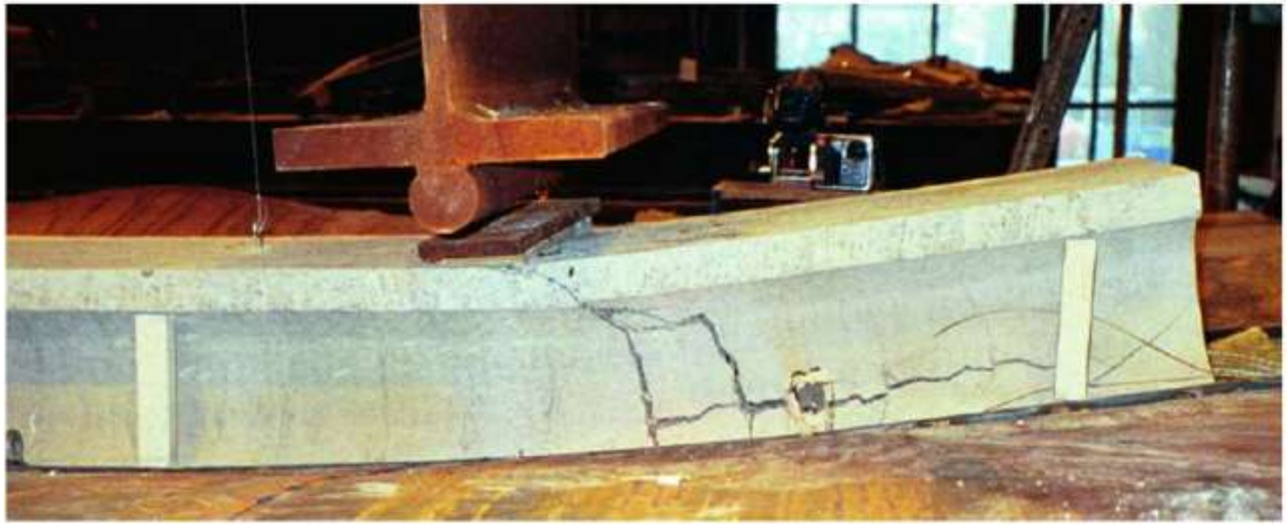
- One test or statistical approach?
  - “In international fire engineering practice, however, still a more traditional way of dealing with structural safety is followed. It is a widely accepted procedure to put only one single specimen of a product to a fire test and approve it if the required time of fire duration is met without failure.
  - Safety with respect to fire is achieved by specifying some safe value at the loading side (duration of the fire) in combination with the recognition that fire in itself has a low probability of occurrence.

Bending and shear+anchorage



Bending and shear+anchorage





Note that test reports many times lacked information

Strand temperatures

- Relevant for design of fire tests by bending capacity
- Nowadays EN1990-1-2 is used
- Strand temepratures are given by Figure A.2

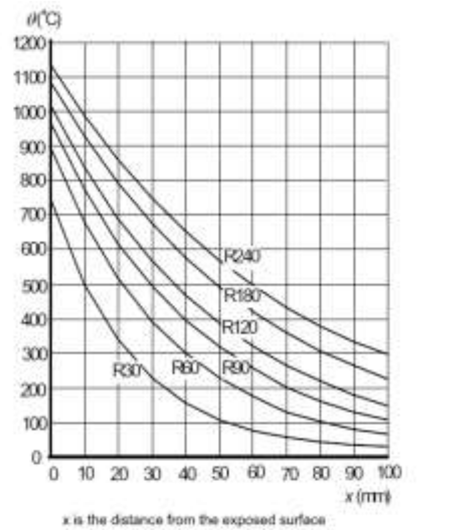
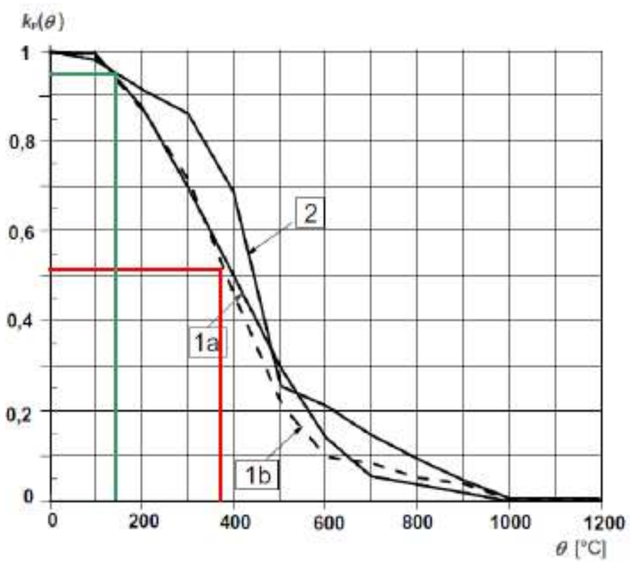


Figure A.2: Temperature profiles for slabs (height h = 200) for R60 - R240

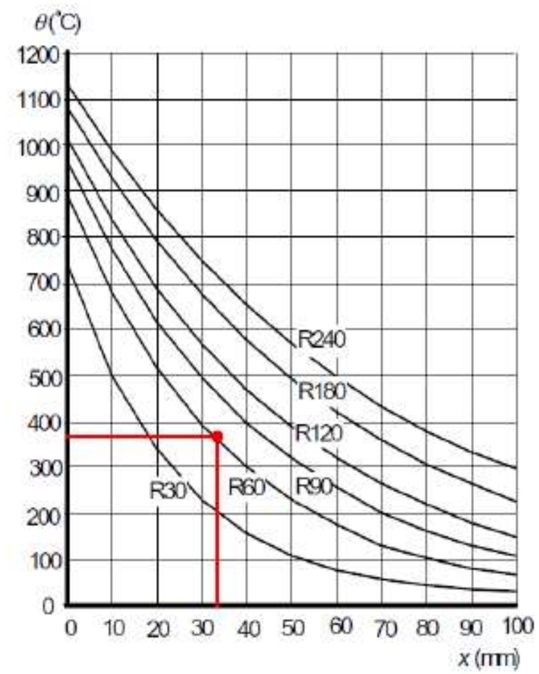
H#	Test ID	Measured T [°C]	Calculated T [°C]	Axis distance	time [min]	ΔT (M/C) [%]
H3	FROSI 4904	500	474	38	120	105,5%
H4	VTT PAL 1927	470	402	36	80	116,9%
H14	VTT PAL 2163/72	297	339	36	61	87,6%
H15	VTT PAL 6710/73	360	405	39	90	88,9%
H18	VTT PAL 7116-74	238	345	35	60	69,0%
H21	VTT PAL 1376/77	253	345	35	60	73,3%
H27	VTT PAL 9498	355	319	35	50	111,3%
H31	VTT PAL 1146b	360	373	45	88	96,5%
H32	VTT PAL 1191	341	371	45	112	91,9%
H33	VTT PAL 1350	309	298	45	78	103,7%
H34	VTT PAL 1038a	352	322	55	105	109,3%
H35	VTT PAL 1038b	279	295	33	45	94,6%
H36	VTT PAL 1038c (prt)	94	119	33	262	79,0%
H37	VTT PAL 1275a	297	262	65	105	113,4%
H38	VTT PAL 2358	380	372	38	64	102,2%
H40	VTT PAL 2481	446	376	38	78	118,6%
H46	**VTT PAL 4337**	401	369	33	62	108,7%
H50	VTT PAL 4452	542	560	33	135	96,8%
H51	VTT PAL 4453	438	354	34	60	123,7%
H56	VTT PAL 566b	399	327	37	60	122,0%
H59	VTT PAL 5308	325	384	31	61	84,6%
H62	VTT PAL 5377	442	431	34	83	102,6%
H74	VTT PAL 00360/90a	377	351	56	120	107,4%
H75	VTT PAL 00360/90b	363	351	56	120	103,4%
H76	VTT PAL 1126/91	352	420	55	157	83,8%
					AVG	99,8%
					CoV	14,9%

Bending capacity calculation

H#	Test ID	R [min]	Slab Depth [mm]	Topping [mm	Axis [mm]	A_p [mm^2]	FeP	T [°C]	$k_{p\theta}$	$M_{R,fi}$ [kNm]	$M_{S,fi}$ [kNm]	$M_{S,fi}/M_{R,fi}$ [%]	
H46	VTT PAL 4337	62	265	0	33	312	1860	369	**0,541**	**59,1**	**58,1**	**98,3%**	Class B
								β=0,984	0,562	64,4	58,1	90,0%	Class A



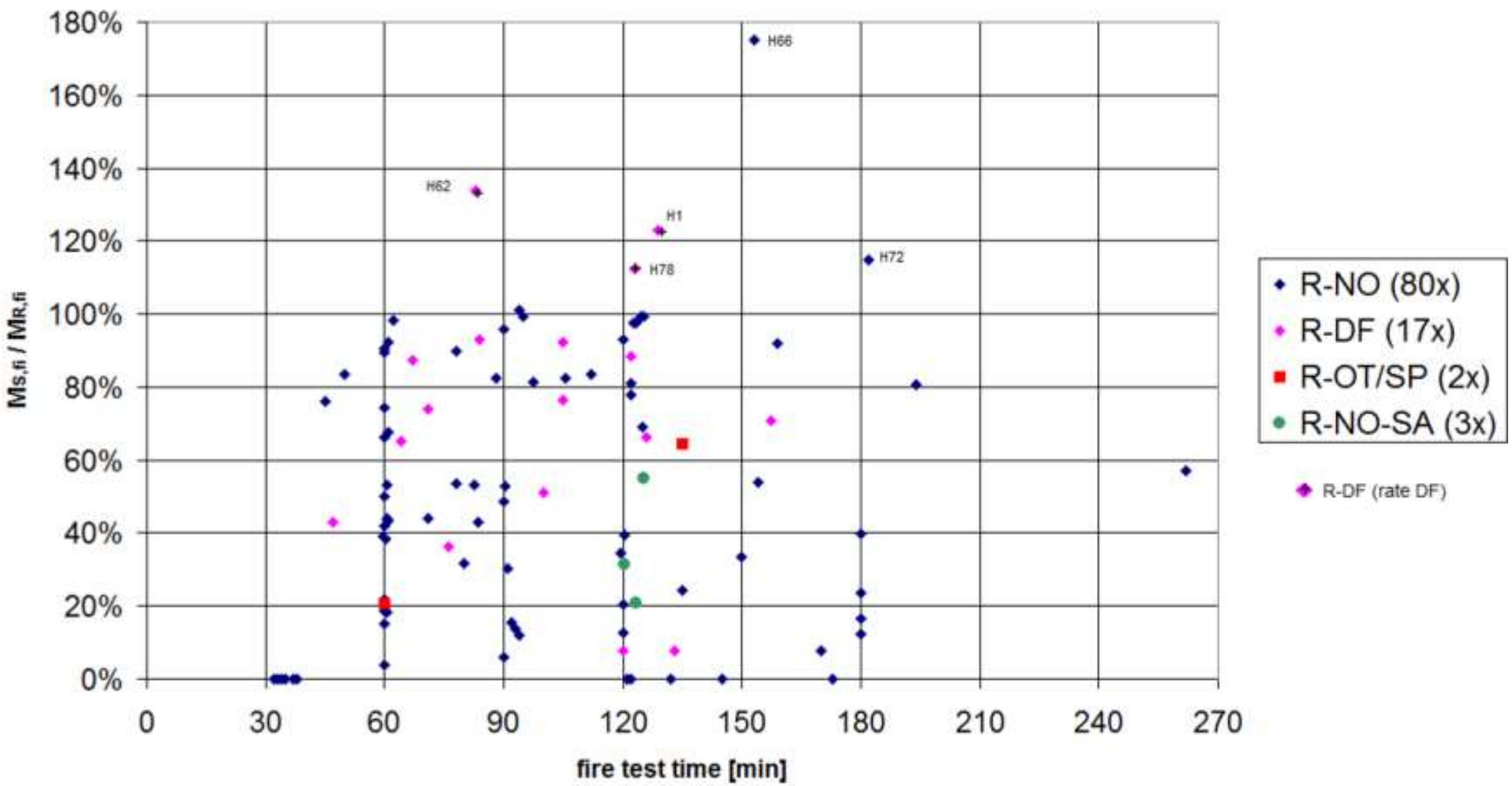
H46



Kuva 4. Koeaika 60 min.

Bending moment / bending capacity fire

- In 96 tests bending moment / capacity < 100%
- Only 6 tests > 100%, but 3 of these did not fail



Remark regarding bending failure

Some tests were stopped when deflection reached L/30, but:

- EN1363-1 Fire tests – Failure to support the load is deemed to have occured when both of the following criteria have been exceeded for flexural loaded elements

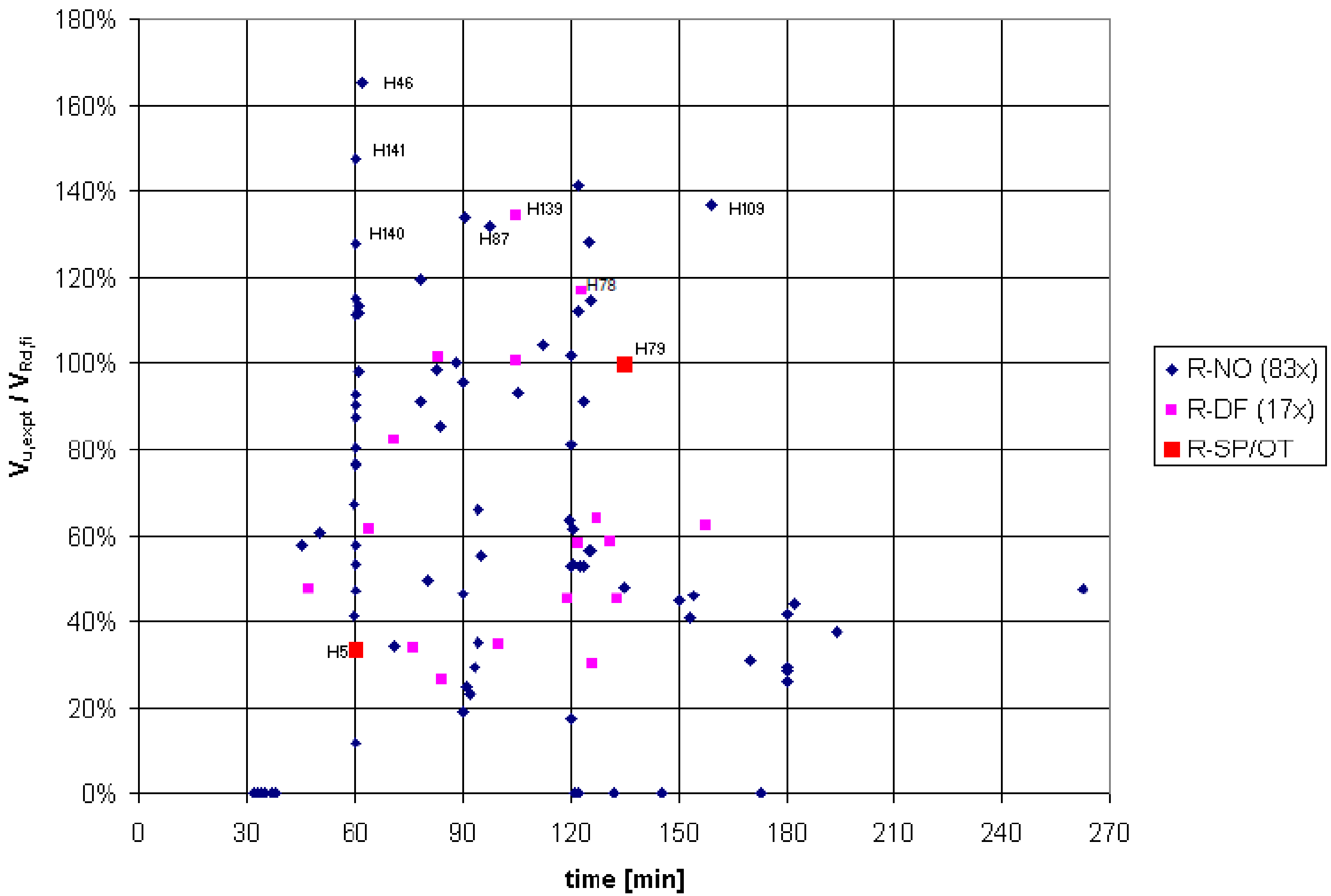
Limiting deflection	$D = \dfrac{L^2}{400d}$	*[mm]*
Limiting rate of deflection	$\dfrac{dD}{dt} = \dfrac{L^2}{9000d}$	*[mm/min]*

- Exceeding the deflection: in case of d = 265 mm and L = 5000 mm
  - $L^2/400d = 235$ mm
  - $L/30 = 167$ mm
  - Tests were stopped too early, according to standard R not reached
- Exceeding the limit rate of deflection: means that specimens were on onset of a bending failure

Reviewers

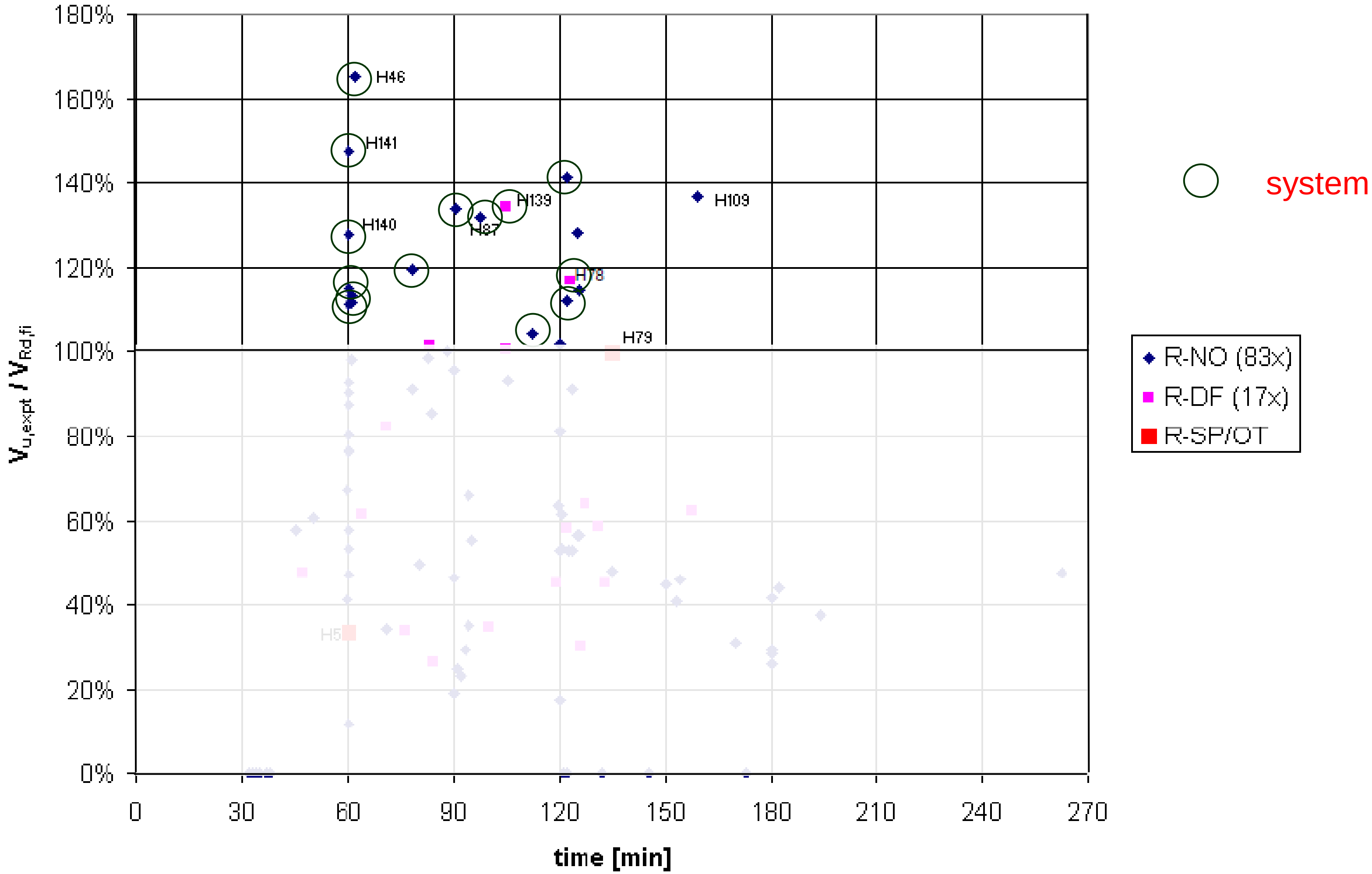
- "In the set of 162 tests no test were indicated as having failed by exceeding the bending capacity".
- "However, in the report it is argued that a number of tests, which were stopped because of exceeding the specified limit rate of deflection, were at the onset of producing bending failures. The reviewers accept this argument".
- "It should be noted that the bending failure mode has never been subject of a serious dispute".

Shear load / shear capacity fire



- In 80 tests shear and anchorage load/capacity <100%
- Only 22 tests > 100%, but did not fail

Shear load / shear capacity fire

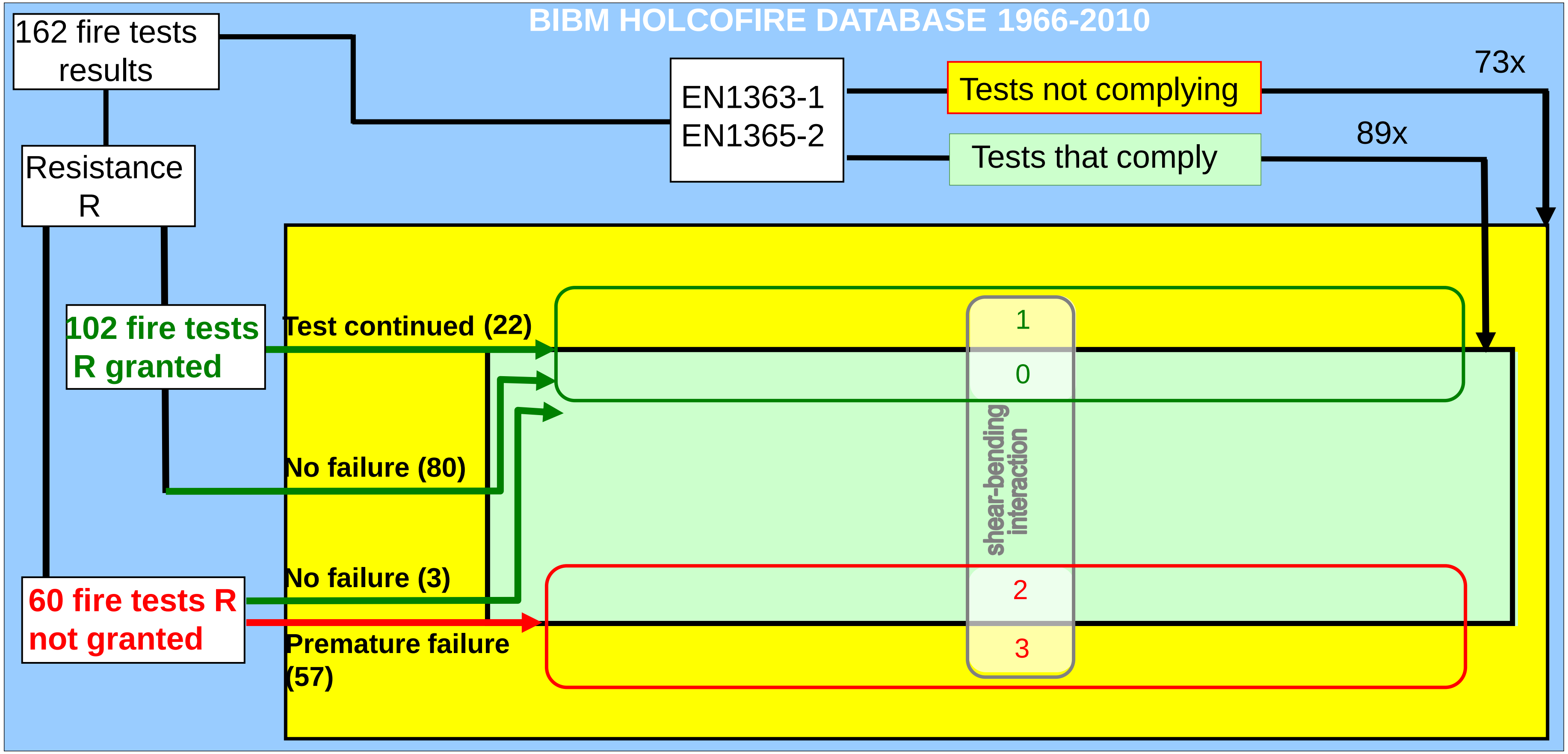


- Those above 100% are mainly systems

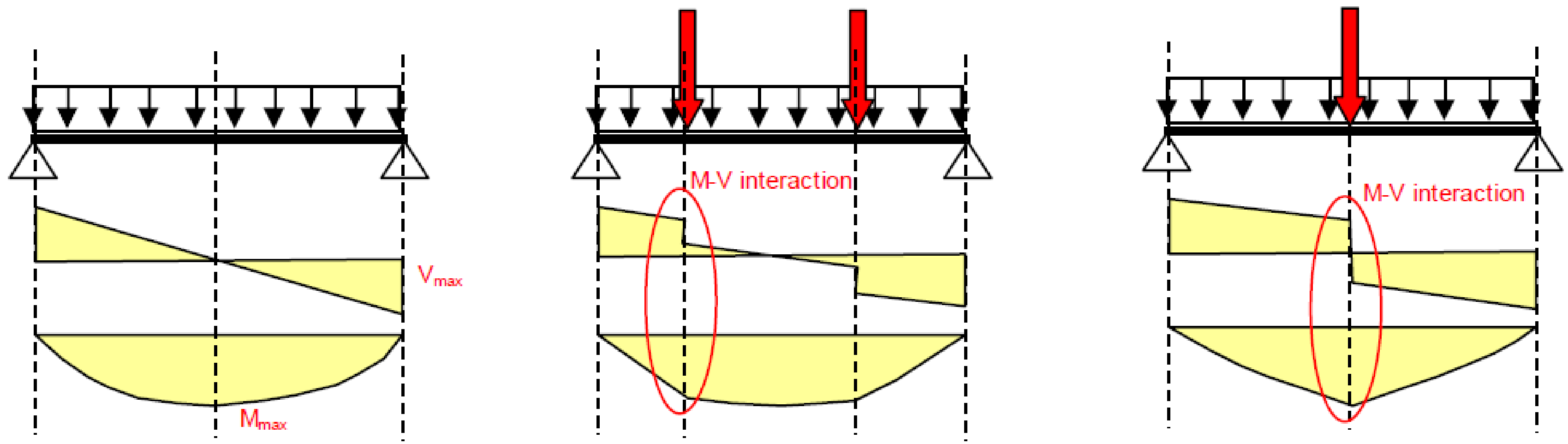
Reviewers

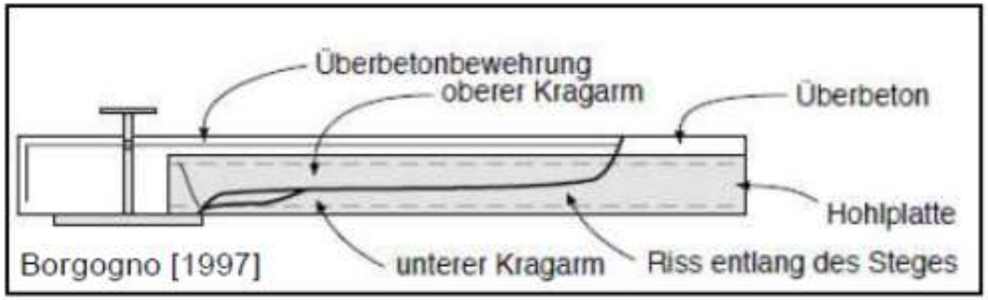
- "...in a considerable number of other tests the expected shear/anchorage failure was not reached, for instance because of the fact that the test was stopped since the required time had been reached. For the case of shear/anchorage capacity 92 tests of this type were selected.".
- "It turns out that the mean ratio V_{exp}/V_{calc} is about 1.0 for single slabs and 1.29 for slabs being a part of a floor system. The coefficients of variation for V_{exp}/V_{calc} are 22 % and 24 % respectively, for single slabs and slabs being a part of a larger floor system (with restraint action at the boundaries) . This seems high though acceptable".
- "Restraint effects always seem to be important, but also they are not a part of the formula".

Fire tests with shear-bending interaction (6x)



H88 – CTICM 95-E-467





Shear-bending interaction

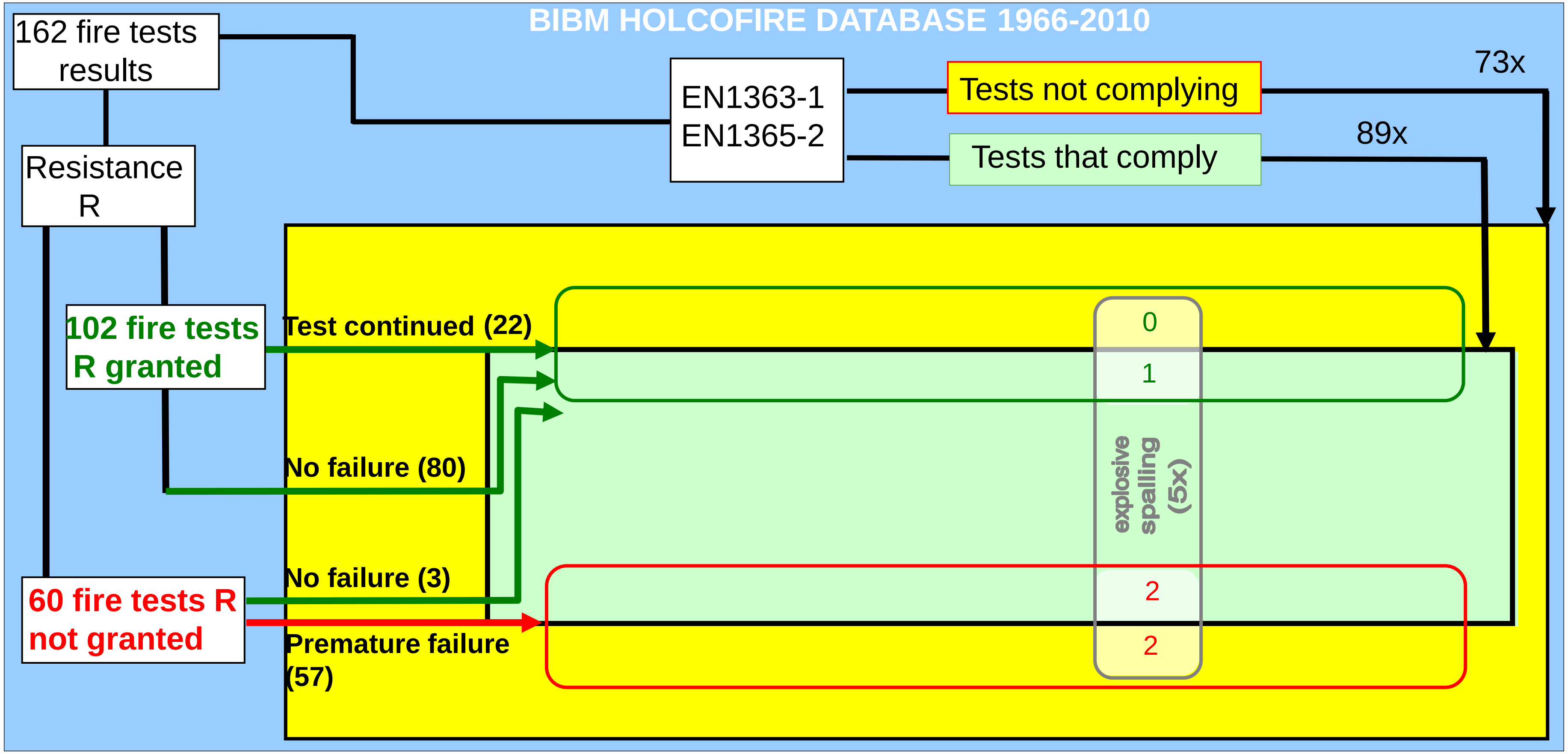
H20: 0.95
H80: 1.38
H88: 1.15
H90: 1,56
H91: 1,13
H113: 1.33

$$\frac{V_S}{V_{R,fi}} + \frac{M_S}{M_{R,fi}} + \cancel{\frac{T_S}{T_{R,fi}}} \leq 1.0$$

Reviewers

- “For this failure mode, which can be regarded to be in the transition range between flexural-shear and anchorage failure only 6 relevant tests could be found. Actually this requires the statistical uncertainty to be taken into account. An interaction formula is given, showing a mean value and standard deviation which are fair enough. It might be wondered if this is really needed, since the lowest bearing resistance obtained from the separate equations for bending and shear may be expected to give a reasonable design value as well”.

Fire tests with explosive spalling (5x)



Fire tests with spalling


Spalling during the fire test

Part of hole that occured at 39 minutes

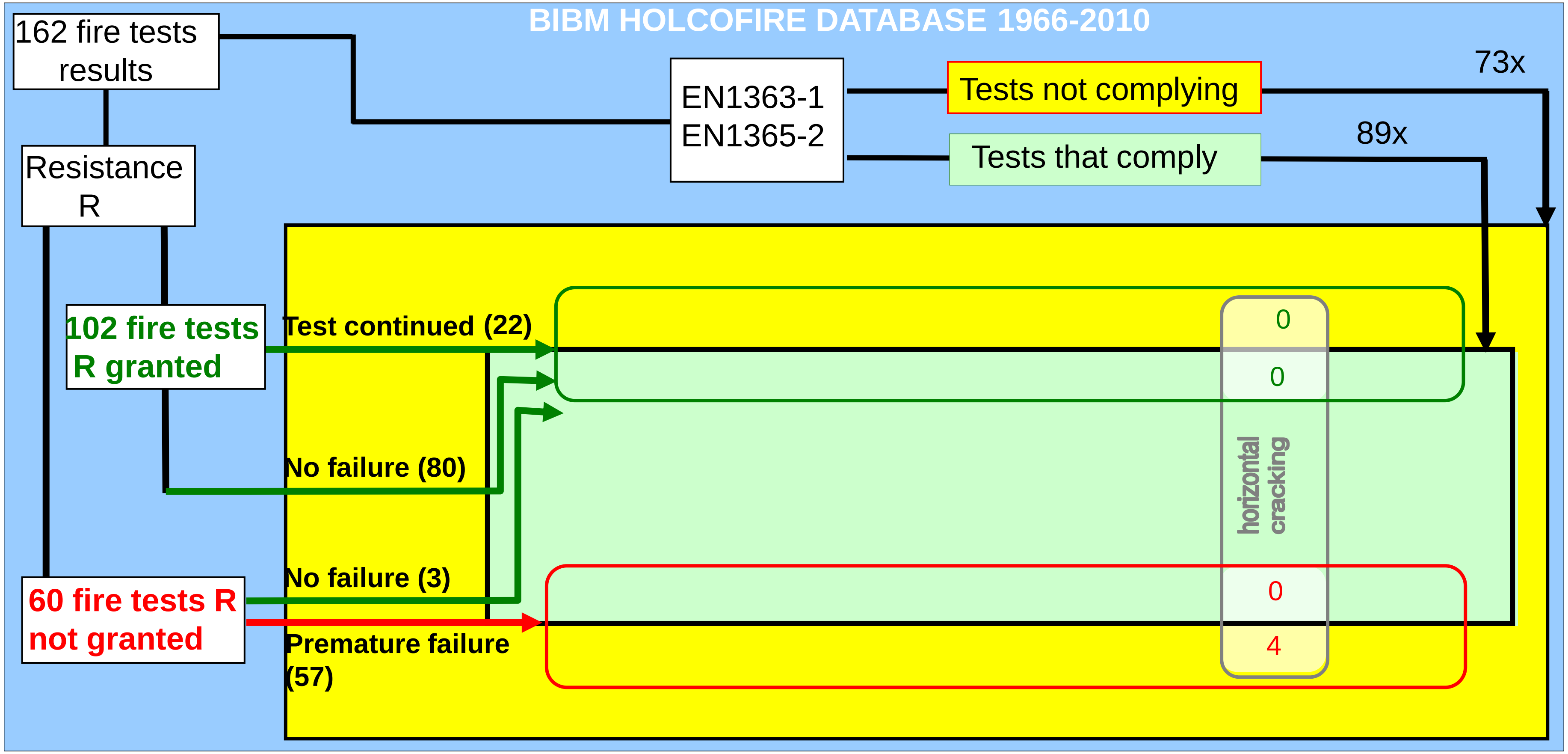
Fire tests with spalling

- Moisture content unknown or under 3%
- Mostly systems, one with LWC

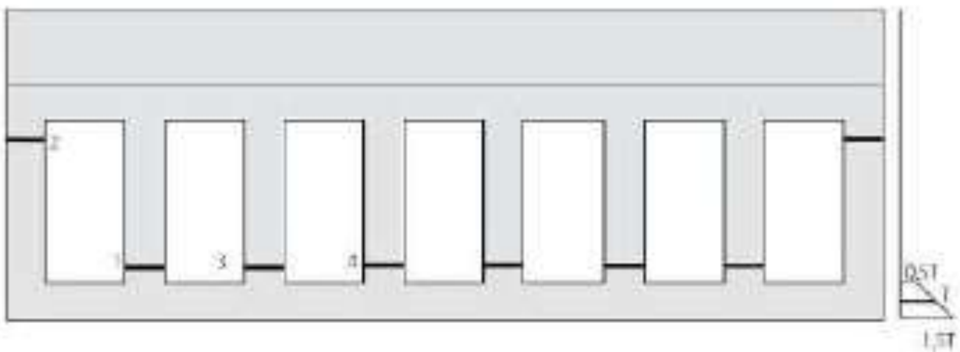
no	test ID	test year	depth	Top ping [mm]	avg axis dista nce [mm]	Expoed length test set up [m]	tested width of set-up [m]	Test set-up	EN 13 65-2	R test result [min]	Failure after fire
H5	VTT PAL 2892	1971	265	0	36	5,63	2,4	SYS	1	60	R-SP
H57	VTT PAL 566c	1985	265	0	36	5,165	2,4	SYS	1	39	SP
H60	VTT PAL 5327	1985	265	0	63	5,175	2,4	SYS	1	66	SP
H103	DIFT COWI PG 10724	2000	220	80	36	6,14	2,4	SYS	0	25	SP
H136	UP HPLWC	2004	200	0	1	4	2,4	HCS	0	76	SP

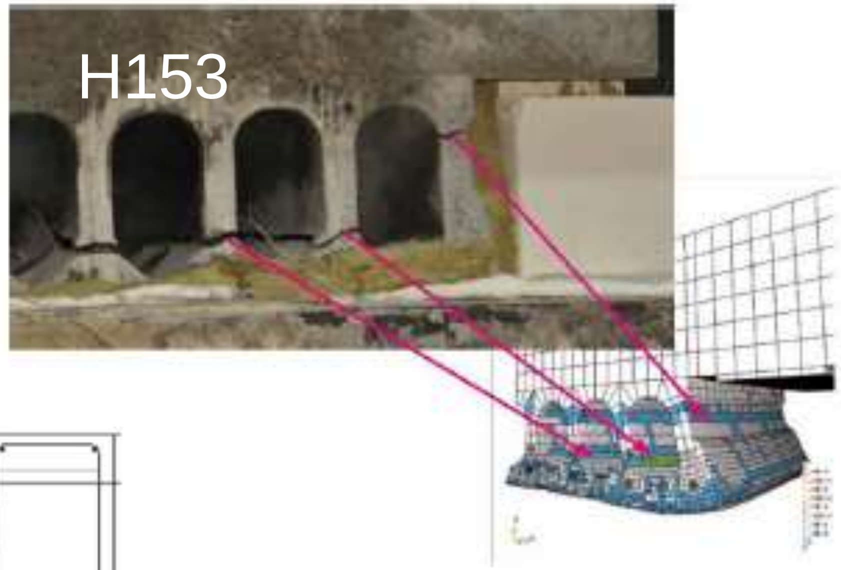
- H5: VTT PAL 2892 [1971] - age unknown days - unknown moisture content
- H57: VTT PAL 566c [1985] - age 176 days - 2.5 to 3.0 %
- H60: VTT PAL 5327 [1985] - age 133 days - 2.8 to 2.9%
- H103: DIFTCOWI PG10724 [2000] - age 74 days - unknown moisture content
- H136: UP HPLWC [2004] - age 817 days - unknown moisture content

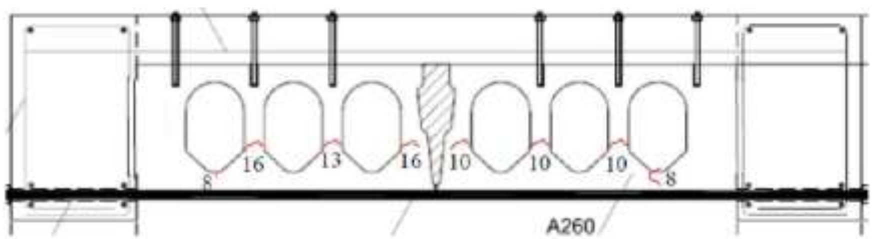
Fire tests with horizontal cracking (4x)



Specific Dutch tests on slices

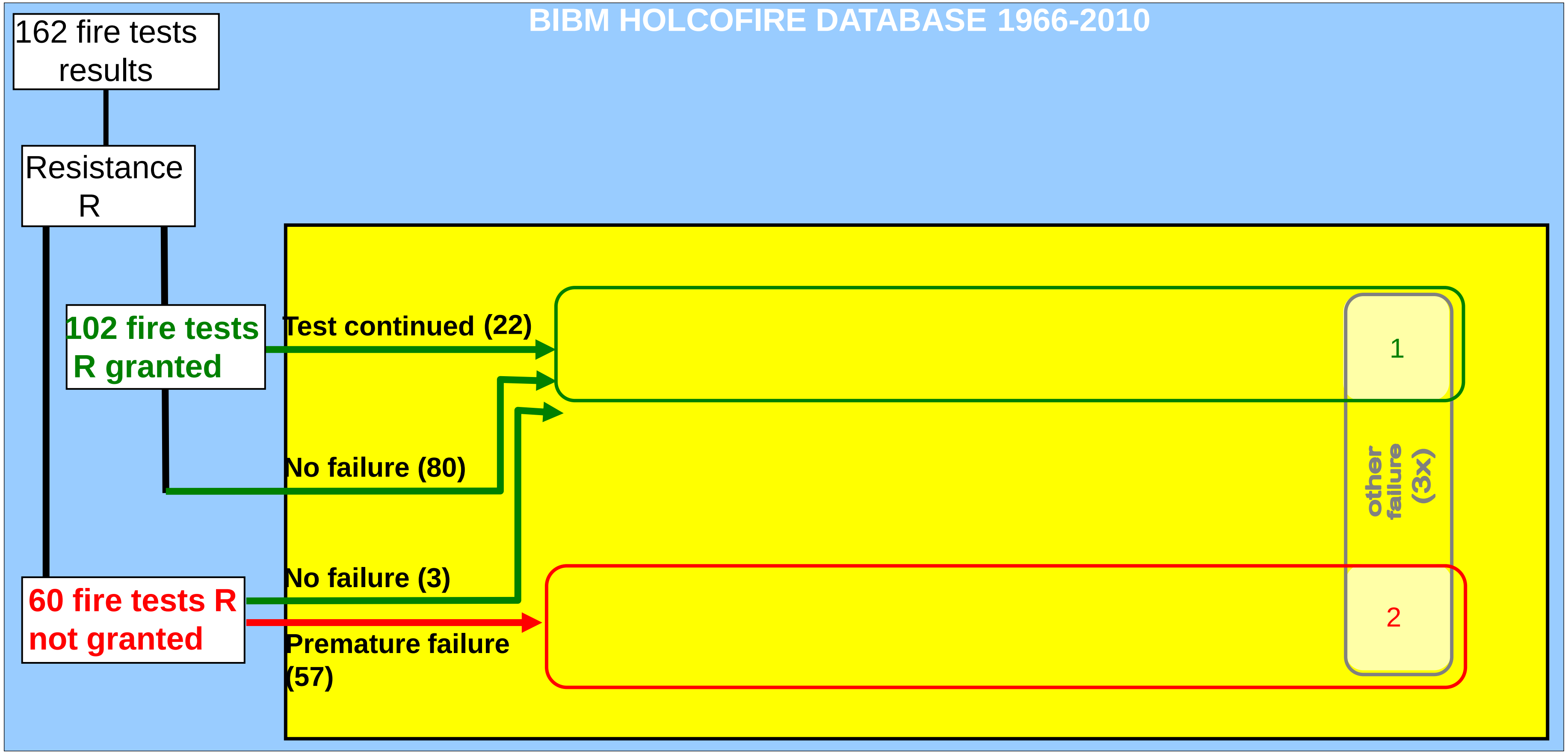






To be addressed by Ronald Klein-Holte tomorrow

Other failure types (3x)



Other failure types

no	test ID	test year	depth	Top ping [mm]	dista nce [mm]	Expoed length test set up [m]	tested width of set-up [m]	Test set-up	EN 13 65-2	R test result [min]	Failure after fire
H52	VTT PAL 4454	1985	265	0	64	5,185	2,4	SYS	1	43	OT
H79	IBS 3350/93	1993	265	0	35	4,1	2,4	SYS	1	135	R-OT
H84	EMPA B2-3	1995	200	0	30	4,7	2,4	SYSB	1	74,6	OT

H52: bond defect (15.2 mm strands used)
H79: 135 min, but failure type not reported
H84: punching shear

Conclusions database

- The meta-analyses show very detailed insight in failure types of hollow core slabs/floors in a fire test
- The main failure types observed under fire in the database are:
  - bending failure exhibited by exceeding rate of deflection (11x);
  - shear and anchorage failure (42x);
  - shear-bending interaction failure (6x);
  - explosive spalling (5x);
  - horizontal cracking (4x),
  - and other uncommon failure types (3x).
- 94,5% of the database fire test results can be explained with the design models and requirements stated in the available European standards (EN1992-1-2, EN1168, EN1363-1, EN1365-2).

Reviewers

- “The gathering and evaluation of all test data can be considered a very valuable initiative. The reviewers consider the contents of this report as a fair description and interpretation of the authentic 162 fire test results”.
- “The statistical evaluation shows that within the normal context of actual fire safety engineering bending and shear predictions by Annex G can be classified as acceptable”.

Conclusions database

- 5,5% of the fire test results in the database, mainly related to explosive spalling and horizontal cracking, cannot be explained fully today (May 2013).
- The phenomena are not yet fully understood (may 2013), although it becomes clear from the fire tests that moisture content, thick topping, and floor restraints are important influencing parameters.
- Therefore, (explosive) spalling and horizontal cracking remain subjects for further research in the Holcofire project in the year 2013 → reported on tomorrow in Technical Seminar day 2

Reviewers

- “The reviewers agree with the conclusion that the collection of fire tests regarded does not give enough information on the effect of structural toppings nor effects of restraints, and that the mechanisms spalling and horizontal cracking still require further research”.

Thank you for your attention

The work of Manhal Said from Consolis Technology on setting up the database and performing MathCAD Annex G calculations is highly acknowledged