F.R. Note No. 95/1954
Research Programme
Objective E/3/7(P)

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

THE SCALING OF DIMENSIONS IN B.S. 476 FIRE-RESISTANCE TESTS

by

J. H. McGuire

Summary

An electrical analogue of heat conduction (1) has been used to investigate the relation between the dimensional scale of a structure and the time required for a point within it to attain a specified temperature, when the structure is tested for fire-resistance in accordance with B.S. 476. The effects of such factors as the presence of water in a structure are discussed. Tables are given relating time and dimensional scaling factors, and the limitations in their application are indicated.

F.

January, 1954.

Fire Research Station,
Boreham Wood,
Herts.

THE SCALING OF DIMENSIONS IN B.S. 476 FIRE-RESISTANCE TESTS

by

J. H. McGuire

1) Introduction

The furnace testing of elements of structures (such as walls, columns, beams and floors) in accordance with the fire-resistance test of B.S. 476 incurs considerable expense and involves specialized and very expensive equipment. It would therefore be valuable if, from the result of a test on any structure, the result to be expected from similar structures of different scales could be calculated.

By using an electrical analogue (1) to solve a number of problems, tables have been derived which relate the dimensional scales of structures and the times to attain specified temperatures.

In the first instance, these tables are only applicable to fire-resistance tests on structures which are not damaged by fire and in which conduction is the only heat transfer process taking place. In a previous note, however, (2) it has been shown that a number of processes which occur in problems described broadly as "thermal conductivity" problems obey laws similar to those governing thermal conductivity. The occurrence of these processes, described in paragraph 4, does not therefore, invalidate the use of the tables.

The practical application of the tables assumes that the general behaviour of the structure about which predictions are being made will be the same as that of the structure tested. This assumption must be justified. An example where this assumption was fallacious is described in paragraph 4. Four scales of prestressed concrete beam were tested and only in the largest did the concrete cover to the prestressing wires fall away during the test. The result for this beam was not therefore related to the others as would be expected from Table 2. The result was not due to unusual circumstances and it is found, in fact, that such falling away can be expected where large thicknesses of concrete cover are used without reinforcement.

2) Definition of "scaled structures"

For the purposes of this note one structure is considered to be a scaled replica of another if all dimensions in which there is a component of heat flow in the one structure are related to the corresponding dimensions in the second structure by the same factor. Dimensions in which there is no component of heat flow do not influence the thermal problem and may be related by other factors. Thus in a cylindrical problem, in which transfer occurs radially, the height of a specimen may be considered scaled by any convenient factor. Similarly, in a problem involving a wall consisting of laminae of one or more materials, all heights may be considered scaled by one factor whilst a different factor may be applied to widths.

3) Fire-resistance scaling tables

Table 1 relates the times for a temperature rise of 140°C to occur on the unexposed faces, to the dimensional scales, of walls or bulkheads subjected to fire-resistance tests in accordance with B.S. 476.

Table 2 relates the times for temperature rises of 150°C to 400°C to occur at the centres, to the dimensional scales, of columns subjected to fire-resistance tests in accordance with B.S. 476. As mentioned in the Introduction there are limitations in the application of the tables and these are detailed in paragraph 4.

The following example illustrates the use of the tables. Suppose a 4 inch wall, subjected to a B.S. 476 furnace test, failed in 81 minutes because the temperature of the unexposed face rose by 139°C and supposing the failure time of a similar 6 inch wall, subjected to the same test, were required. The dimensional scaling factor is 6 ÷ 4 = 1·5 and as 81 minutes lies between 1 hour 10 minutes and 1 hour 40 minutes Table 1 gives the result that the time multiplication factor would be 1·98. The 6 inch structure would therefore have a fire-resistance time of 1·98 x 81 = 160 minutes = 2 hours 40 minutes, failure again being defined as due to a temperature rise of 139°C at the unexposed face.

Where time predictions are being made concerning temperatures at the centres of walls or bulkheads the cooling to the atmosphere at the unexposed face scarcely influences the problem and Table 2 will be found applicable.

Where temperatures at points in columns other than the centre are being considered, it was found by the use of the analogue, that time multiplication factors greater than unity given by Table 2 needed to be reduced and those less than unity increased (by up to 20 per cent depending on the point considered). The structures about which analogue predictions were made in order to derive the tables, are listed in Appendix 1.

4) Limitations in the application of the tables

The principal limitation in the practical application of the tables is that it must be known that the general behaviour of the structure about which predictions are to be made will be the same as that of the structure tested. The importance of this factor is best illustrated by Table 3 which lists the failure times of four scales of a type of prestressed concrete beam together with predicted times based on one particular result. Failure was actually by collapse but the tables were applicable because it was found that collapse occurred when the prestressing wires attained a specified temperature. The table derived for columns (Table 2) was used because the conditions at the prestressing wires closely resembled those at the centre of a column, there being no cooling to the atmosphere.

Table 3

Predicted failure times of prestressed concrete beams

Scale of beam	Actual fire-resistance time	Fire-resistance time predicted from $\frac{1}{2}$ scale result
4/5	165 minutes	226 minutes
1/2	*100 "	100 "
3/8	65 "	63 minutes
1/4	38 "	33 "

*Result on which predictions were based.

Order of failing time \ Linear scaling factor	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.70	0.80	0.90	1.10	1.20	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
25 - 35 min.											0.86	1.15	1.30	1.47	1.64	1.81	2.02	2.22	2.43	2.64	2.85	3.29	3.85	4.45	5.05	5.74	6.45	7.28	8.20	9.30	10.60
35 - 50 min.									0.61	0.73	0.86	1.16	1.32	1.49	1.67	1.86	2.08	2.29	2.50	2.74	2.99	3.47	4.09	4.80	5.71	6.61	7.60	8.71	10.10		
50 min. - 1 hr. 10 m.								0.47	0.59	0.71	0.85	1.17	1.33	1.52	1.71	1.91	2.14	2.37	2.61	2.88	3.16	3.73	4.51	5.43	6.60						
1 hr. 10 m. - 1 hr. 40 m.						0.35	0.40	0.46	0.57	0.70	0.85	1.17	1.35	1.55	1.75	1.98	2.22	2.48	2.76	3.08	3.44	4.24	5.31								
1 hr. 40 m. - 2 hr. 20 m.				0.24	0.29	0.34	0.39	0.44	0.56	0.69	0.85	1.17	1.36	1.57	1.79	2.05	2.32	2.62	2.97	3.41	3.94										
2 hr. 20 m. - 3 hr.			0.19	0.23	0.28	0.32	0.37	0.43	0.55	0.69	0.84	1.18	1.38	1.60	1.86	2.14	2.44	2.84	3.25												
3 hr. - 3 hr. 40 m.		0.15	0.18	0.22	0.27	0.31	0.36	0.42	0.54	0.68	0.83	1.19	1.40	1.65	1.93	2.23	2.58														
3 hr. 40 m. - 4 hr. 20 m.		0.14	0.17	0.21	0.26	0.30	0.35	0.41	0.53	0.67	0.82	1.20	1.42	1.69	1.99																
4 hr. 20 m. - 5 hr.	0.10	0.13	0.17	0.20	0.25	0.29	0.35	0.40	0.52	0.66	0.82	1.20	1.44																		
5 hr. - 5 hr. 40 m.	0.09	0.12	0.16	0.19	0.24	0.29	0.34	0.39	0.51	0.65	0.81	1.21																			

TABLE 1 TIME SCALING FACTORS FOR WALLS AND BULKHEADS. B.S. 476 FURNACE CURVE APPLIED
(FAILURE DUE TO TEMPERATURE RISE AT UNEXPOSED FACE)

Order of failing time \ Linear scaling factor	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.70	0.80	0.90	1.10	1.20	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
25 - 35 min.											0.86	1.15	1.31	1.48	1.65	1.84	2.04	2.26	2.46	2.69	2.92	3.42	3.94	4.51	5.08	5.73	6.40	7.10	7.82	8.55	9.40
35 - 50 min.									0.59	0.72	0.85	1.16	1.32	1.50	1.69	1.89	2.10	2.32	2.55	2.80	3.05	3.58	4.15	4.75	5.40	6.09	6.82	7.60	8.50	9.22	
50 min. - 1 hr. 10 m.								0.47	0.58	0.71	0.85	1.16	1.34	1.53	1.73	1.95	2.16	2.40	2.65	2.92	3.18	3.77	4.37	5.05	5.77	6.50					
1 hr. 10 m. - 1 hr. 40 m.						0.34	0.40	0.45	0.57	0.70	0.84	1.17	1.36	1.55	1.76	1.98	2.22	2.44	2.73	3.01	3.29	3.90	4.58								
1 hr. 40 m. - 2 hr. 20 m.				0.24	0.28	0.33	0.38	0.43	0.56	0.69	0.84	1.18	1.37	1.57	1.79	2.02	2.26	2.52	2.79	3.09	3.39										
2 hr. 20 m. - 3 hr.			0.19	0.23	0.27	0.32	0.37	0.42	0.55	0.68	0.83	1.18	1.38	1.59	1.81	2.05	2.30	2.57	2.84												
3 hr. - 3 hr. 40 m.		0.15	0.18	0.22	0.27	0.31	0.37	0.42	0.54	0.68	0.83	1.18	1.38	1.59	1.82	2.06	2.32														
3 hr. 40 m. - 4 hr. 20 m.		0.14	0.18	0.22	0.26	0.31	0.36	0.42	0.54	0.68	0.83	1.19	1.39	1.60	1.83																
4 hr. 20 m. - 5 hr.	0.11	0.14	0.17	0.21	0.26	0.30	0.36	0.41	0.53	0.67	0.83	1.19	1.39																		
5 hr. - 5 hr. 40 m.	0.11	0.14	0.17	0.21	0.25	0.30	0.35	0.41	0.53	0.67	0.83	1.19																			

TABLE 2 TIME SCALING FACTORS FOR COLUMNS. B.S. 476 FURNACE CURVE APPLIED
(FAILURE DUE TO TEMPERATURE RISE AT CENTRE)

It will be noticed that, whilst the predictions for the $^1/_4$ and $^3/_8$ scale beams agree with actual results within the limits of variability to be expected in fire-resistance tests, the prediction for the $^4/_5$ scale beam is quite incorrect. The explanation is that the concrete cover to the prestressing wires fell away from the $^4/_5$ scale beam during the test whilst it remained intact on the others. This behaviour can be expected to be repeatable for it has been found that thicknesses of concrete cover of more than two or three inches require reinforcement to prevent their falling away during test.

In deriving Tables 1 and 2 by the use of the electrical analogue, heat flow within a structure has been assumed to be a process of conduction only. The tables are therefore only applicable where this is the case or where associated processes obey similar laws. A detailed discussion of such processes and other effects is given in a previous note (2) and it is therefore merely necessary to summarise the resulting conclusions.

a) Presence of water in a structure

The principal effect of water in a structure is that it absorbs heat as its temperature rises and as it is vaporized. This effect in no way invalidates the use of the tables, and neither does the fact that water vapour occupies a greater volume than water.

The migration phenomenon encountered in practice is largely a diffusion process and would therefore also not be expected to influence scaling.

b) Cavities and imperfect thermal contact at interfaces

The effect, on scaling of imperfect thermal contact at interfaces may be neglected, as also may the effect of cavities provided, from the geometry of the structure, it can be seen that they do not play a substantial part in the heat transfer through the structure.

c) Variation of thermal properties with temperature

For many materials the quantities thermal conductivity, density and specific heat are functions of temperature. The tables remain applicable in these circumstances.

5) Conclusions

It cannot be overemphasized that the tables should only be used after checking that the limitations described in this note do not apply to the problem under consideration.

6) References

(1) Lawson, D. I. and McGuire, J. H. "The solution of transient heat-flow problems by analogous electrical networks". Proc. Instn. Mech. Engrs., Lond., (A) 1953, 167 (3) 275-487.

(2) McGuire, J. H. "The scaling of dimensions in heat conduction problems". D.S.I.R. & F.O.C. Joint Fire Research Organization F.R. Note No. 94.

APPENDIX 1

List of structures investigated with the analogue

Three inch, $4\frac{1}{2}$ inch and 9 inch brick walls,

3 inch, $4\frac{1}{2}$ inch and 9 inch high conductivity walls,

$\frac{1}{4}$ inch bulkhead protected by $\frac{1}{2}$ inch of concrete on each side, a bulkhead to twice this scale and one to six times this scale,

4 inch diameter steel column protected by $\frac{3}{4}$ inch of concrete and the same scaled up by factors of 2 and 6,

4 inch, 6 inch, 8 inch and 12 inch diameter solid concrete columns.