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NATIONAL BUREAU OF STANDARDS REPORT

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PROPOSED CRITERION FOR DEFINING LOAD FAILURE OF BEAMS, FLOORS, AND ROOF CONSTRUCTIONS DURING FIRE TEST

by

A. F. Robertson
J. V. Ryan

NBS

U. S. DEPARTMENT OF COMMERCE
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Proposed Criterion for Defining Load Failure of Beams, Floors, and Roof Constructions During Fire Test

A. F. Robertson and J. V. Ryan

ABSTRACT

A brief account is presented of procedures used in development of criteria for defining the point at which fire test specimens fail to sustain load during test. It is proposed that both a deflection of $\ell^2/800d$ and an hourly rate of deflection of 5-1/3 times this value be required as an indication of load failure. In these formulae, l is the span between supports in the direction of principle reinforcement and d is the distance between upper and lower extreme fibers of the structural component or assembly.

INTRODUCTION

Recently an investigation was performed on the effect of variations in ceiling fabrication on the fire endurances of a number of floor constructions [1]*. During initial tests in this study it became apparent that in many cases failure might be expected to result from structural effects rather than heat transfer to the unexposed surface. Since, the test procedure used [2] is not specific in defining methods for determining the point at which the specimen fails to "sustain the applied load", it appeared desirable to adopt laboratory procedures which would provide an objective method of determination of this end point. The first attempt at selection of a criterion of load failure, that of fixed deflection of 3 inches [1], was selected for the particular type of floor construction used. It was chosen because it seemed to represent a significant indication of deflection and in addition the data then available, Figure 1, example III, showed that the corresponding rate of deflection was so great that collapse of the construction might be expected to occur rather promptly.

*Numbers in brackets refer to references at the end of the text.

It is evident that a fixed deflection method of specifying the time at which failure to carry the load occurs is not likely to be generally applicable to a wide variety of construction types. This brief paper outlines some considerations made in developing more general criteria of load failure for beam, floor, and roof constructions during fire endurance tests.

LOAD FAILURE CRITERIA

1. Fixed Deflection

The selection of a critical deflection for defining point of load failure, while possibly useful in specific cases, is not applicable to the general case because of differences in specimen construction, span, and materials of construction used. It would be preferable to specify a deflection in terms of the construction design. This was considered but found deficient in properly allowing for variations in longitudinal restraint at the ends of the load carrying members of the construction.

2. Increase in Rate of Deflection

Tests performed in which heavy steel beams were incorporated as load carrying members showed the shortcomings of simple deflection as a criterion of load failure. In tests such as this it was not uncommon to find very large deflections develop without any indication of rapidly increasing rate of deflection with resultant impending collapse. Some analysis of fire endurance data was accordingly made to determine the feasibility of using an increase in rate of deflection as an indication of load failure. Figure 1, example IV, illustrates the method used. The initial nearly constant rate of deflection R_1 was determined and then the time of load failure was assumed to occur at a time when this initial rate had been exceeded by a fixed percentage. In the case illustrated $R_2 = 1.5R_1$. The difficulty with this procedure was largely that of determining the point on the curve at which R_1 was to be measured. Therefore it seemed desirable that the limiting rate of deflection be defined on some other basis, preferably dependent only on the structural features of the design. Also, it seemed apparent that rate of deflection alone was not an adequate criterion.

3. Deflection and Rate of Deflection Method

Previous experience had shown that to be useful a criterion of load failure must be applicable to a variety of construction variables including various types of end restraint, loading, and construction dimensions and materials. The large number and complexity of these variables, not to mention the effects of thermal strains, seem to require a special analysis of each structure. This seemed impractical for the purposes intended and as a result a compromise method was developed. This involves the requirement that both a deflection and rate of deflection be exceeded as an indication of load failure. The requirement of both criteria is believed to provide a practical substitute for detailed analysis of each structure tested.

It can be shown that the maximum deflection of beams involving various types of end support and load application methods is given by the formula:

$$y \max = K \left(\frac{S}{E} \right) \frac{\ell^2}{d}$$

Here:

- K = a numerical constant
- S = working stress
- E = modulus of elasticity
- ℓ = length of beam between supports
- d = depth of beam

This suggests that since permissible values of S, E, and K will be used for design of a structure to be tested, the maximum deflection and rate of deflection which might be considered permissible should be a function of ℓ^2/d. To explore the feasibility of such criteria a number of tests were studied in which a decision had been reached that load failure could be assumed to have occurred. As a result it was decided that the following relationships might well be used for defining time of load failure:

a deflection of $D = \ell^2/800d$ and an hourly deflection rate equal to 5-1/3 times this value or:

$$R = \ell^2/150d$$

To investigate the effect of applying such criteria for identification of time of load failure of structures during fire test a group of 50 experimental data were analyzed. The results are presented in Figure 2. Two columns of data are presented under the main caption "Time to Failure". The first of these entitled "Reported" lists the reported failure time for the construction. In some cases this was limited by load failure, in others by temperature rise, ignition of waste, etc. The second subcaption entitled "New Criteria" indicates the time at which load failure would be indicated by application of the criteria proposed. In cases where heat transfer etc. limits performance the endurance would be shorter than the values shown in this column. The column entitled "Net Change of Fire Endurance" indicates the change which would occur on application of the proposed criteria. The entries here recognize the fact that in some cases temperature rise, etc., may limit endurance. In other respects the table is believed to be self explanatory.

Study of the table indicates that application of the criteria to the specimens listed would have the effects of increasing the endurance in 13 instances, reducing it in 13, and in 24 instances there would either be no effect or it would be uncertain. It thus becomes evident that use of the criteria is quite successful in selection of load failure times which are reasonably consistent with behavior as analyzed by the operator in charge of the test. The requirement that both a given deflection and rate of deflection be achieved is believed to present a useful method of defining the point of load failure of beams, floors, and roof constructions tested on end supports but regardless of the type of restraint applied at these ends.

CONCLUSIONS

The investigation performed seems to justify use of the following criteria for defining the time at which a specimen should be considered as having failed to sustain the load during a fire test.

A beam, floor, or roof construction mounted on end supports and subjected to a fire endurance test will be considered to fail to sustain the applied load when both

the net deflection resulting from fire exposure has exceeded $\ell^2/800d$, and the hourly rate of deflection has exceeded 5-1/3 times this deflection.

In these formulae:

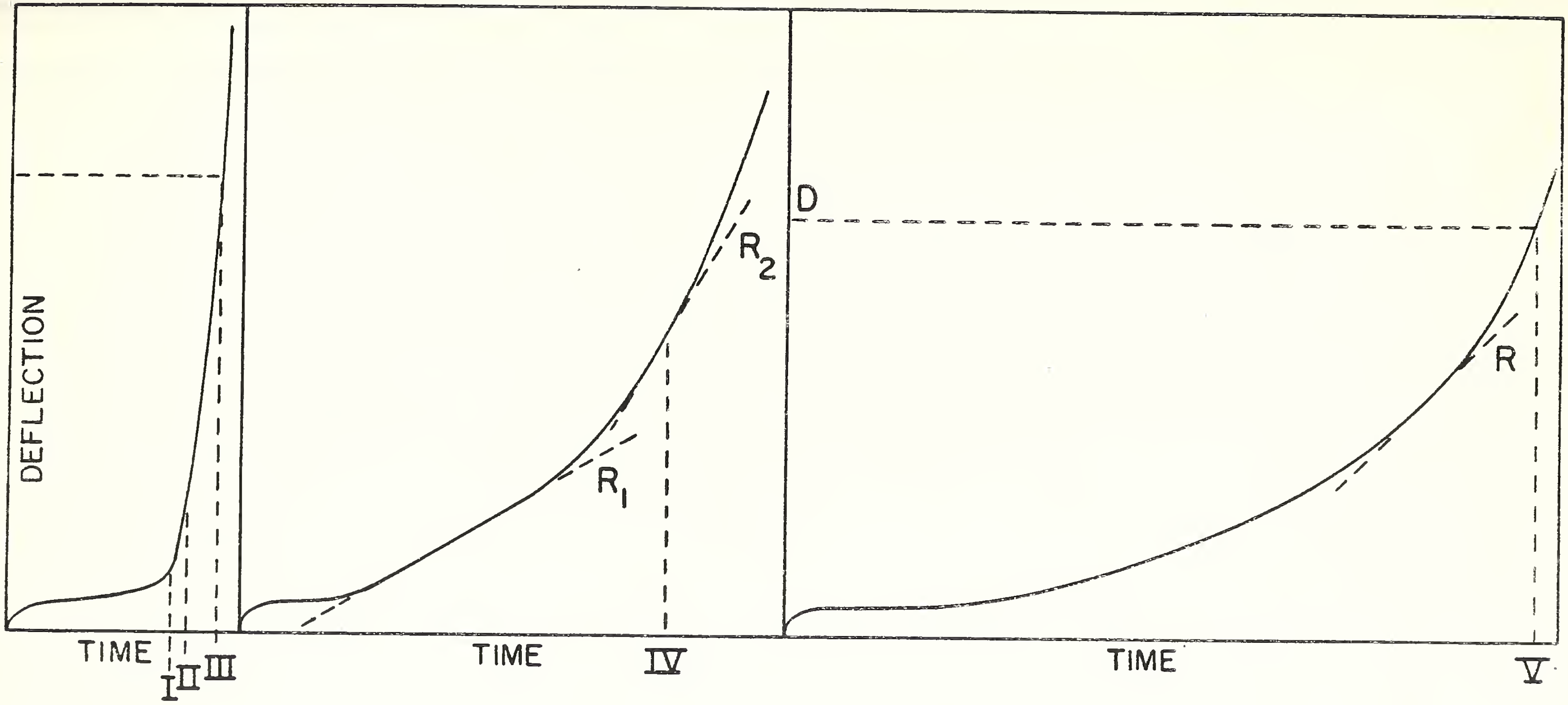
ℓ is the span of the structural component between supports and in the direction of the principle reinforcement or structural element.

d is the distance between the upper and lower extreme fibers of the structural component or assembly.

REFERENCES

[1] "Fire Endurance of Open-Web Steel-Joist Floors With Concrete Slabs and Gypsum Ceilings" by J. V. Ryan and E. W. Bender, Building Materials and Structures Report 141, 1954, U. S. Government Printing Office.

[2] "Standard Methods of Fire Tests of Building Construction and Materials", ASTM Designation E-119, ASTM Standards.



I SUDDEN CHANGE

II RAPID INCREASE

III FIXED DEFLECTION

IV DEFLECTION RATE RATIO

$R_2 = KR_1$

(K=1.5 USED)

V DEFLECTION PLUS RATE: BOTH REQUIRED; VALUES GIVEN BY—

$D = L^2/800d \quad R = L^2/150d$

WHERE L AND d ARE DIMENSIONS OF SUPPORTING ELEMENTS

FIG. 1 — DEFLECTION CURVES AND CRITERIA REPRESENTATIONS

This table compares the times of failures, as determined by the appropriate testing personnel, in tests of several types of floor constructions with the times derived by examination of the test data in accord with the proposed load failure criterion. This criterion defines load failure time as that time when a deflection $D = \ell^2/800d$ and rate of deflection $R = \ell^2/150d$ hr have both been attained or surpassed. In these formulae, ℓ = clear span, d = depth to most remote stressed fiber. Most of the data are from tests performed before these formulae were considered.
Note: Times in parentheses, ( ), indicate no data after the given time, although given deflection or rate not attained, net changes in ( ) correspond to these times.

Construction	Failure Criterion	Dimensions ℓ ft:in.	Dimensions d in.	Deflection at Failure: Deflection in.	Deflection at Failure: Rate in./hr	Criteria $\ell^2/800d$ in.	Criteria $\ell^2/150d$ in./hr	Time Criteria Reached $\ell^2/800d$ hr:min	Time Criteria Reached $\ell^2/150d$ hr:min	Time to Failure: Reported hr:min	Time to Failure: New Criteria hr:min	Net Change of Fire Endurance min	Time to Temperature Limits Rises on Unexposed Surface 250 deg F av hr:min	325 deg F max hr:min
Floors, Wood Joist														
ML, GP	Load failure	12:10	9.75	14.	310.	3.04	16.2	0:47	0:47	0:51	0:47	-4	(0:50)	(0:50)
ML, GP	do	12:10	9.75	8.3	123.	3.04	16.2	1:08	1:06	1:12	1:08	-4	(1:10)	(1:10)
ML, PP	do	12:10	9.75	5.7	25.+	3.04	16.2	0:57	1:00	1:06	1:00	-6	(1:05)	(1:05)
ML, LP	Collapse	12:10	9.75	16.+	1150.+	3.04	16.2	0:26	0:19	0:29 1/2	0:26	-3 1/2	(0:30)	(0:30)
GB	Surf temp	12:10	9.75	9.1	468.	3.04	16.2	0:40	0:37	0:38	0:40	0	(0:45)	0:38
ML,GP	Load Failure	12:10	9.75	3	9.+	3.04	16.2	1:44	(1:44)	1:44	(1:44)	?	(1:40)	(1:40)
ML,GP	do	12:10	9.75	3.3	6.0	3.04	16.2	1:57	(2:00)	2:05	(2:00)	?	(2:00)	(2:00)
Steel Joists														
SJ103,GS,GL,GP	Rapid defl	12:10	10	2.5	33.	3.0	16.0	1:50	1:46	1:48	1:50	+2	(1:50)	(1:50)
SJ103,GS,GL,GP	do	12:10	10	1.2	30.	3.0	16.0	1:44	1:39	1:40	1:44	+4	(1:45)	(1:45)
SJ103.GS.GL.GP	3 in. defl	12:10	10	3.0	16.0	3.0	16.0	2:06	2:06	2:06	2:06	0	(2:30)	2:26**
SJ103.GP1,GL,GP	do	12:10	10	3.0	47.	3.0	16.0	1:07	1:03	1:07	1:07	0	(1:10)	(1:10)
SJ103,CS,GL,GP	Surf temp	12:10	10	3.0	12.	3.0	16.0	6:40	6:42	4:25	6:42	0	4:25	4:46
SJ103. do	do	12:10	10	3.0	4.8	3.0	16.0	4:12	4:21	3:14	4:21	0	3:14	3:19
SJ103, do	3 in. defl	12:10	10	3.0	33.	3.0	16.0	1:06	1:01	1:06	1:06	0	(1:10)	(1:10)
SJ103, do	Surf temp	12:10	10	3.0	20.	3.0	16.0	2:54	2:50	2:44	2:54	0	(3:00)	2:44
SJ103. do	3 in. defl	12:10	10	3.0	10.8	3.0	16.0	1:51	1:54	1:51	1:54	+3	2:01	1:59
SJ81, do	Rapid defl	8:0	8	1.4	3.0	1.44	7.7	2:17	(2:17)	2:15	(2:17)	(+2)	2:48	2:40
SJ102,BR,ML,GP	3 in. defl	12:10	10	3.0	10.1	3.0	16.0	1:24	1:26	1:24	1:26	+2	(2:45)	2:38
Precast Concrete Joists														
CS, Joists embedded	Hole through	12:10	9.25	3.6	12.	3.2	17.1	0:33	0:40	0:35	0:40	0	(0:35)	0:36
CS, Joists embedded.GB	Excess defl	12:10	9.25	4.9	18.	3.2	17.1	0:53	0:52	0:57	0:53	-4	1:10	1:13
CS, Joists embedded	Surf temp	12:10	9.0	5.9	15.6	3.3	17.6	0:39	0:38	0:48	0:39	-9	0:48	0:51
Slabs														
Tile & concrete	Collapse	18:0	7.0	Collapse		8.34	44.4	1:10	1:10	1:10	1:10	0	(1:05)	(1:05)
Tile & concrete,GP	Waste ign	12:10	4.375	3.2	2.2	6.78	36.1	3:23	(4:07)	2:27	(4:07)	0	3:08	2:58
CC	Rapid defl	12:10	5.25	5.1	14.	5.65	30.1	0:47	0:51	0:45	0:51	+6	(1:00)	(1:00)
Steel Decks														
Cell, c, w, CF	Surf temp	9:6	5.1	2.4	1.2	3.2	16.9	(6:53)	(6:53)	4:45	(6:53)	0	4:45	4:53
Cell. do	do	7:0	5.6	0.8	0.1	1.6	8.4	(6:47)	(6:47)	3:20	(6:47)	0	3:20	3:34
Cell. do	Rapid defl	8:0	5.6	1.7	1.1	2.06	11.0	3:18	(3:25)	3:00	(3:25)	(+25)	(3:30)	3:30
Cell. do	Surf temp	8:0	5.6	0.8	0.1	2.06	11.0	(7:00)	(7:00)	5:03	(7:00)	0	5:03	5:06
Form. c, BR, GP	do	4:8	1.5	1.5	3.9	2.7	14.3	(2:10)	(2:10)	1:52	(2:10)	0	1:52	1:57
Form. do	Flame through	4:8	1.5	3.9	15.+	2.7	14.3	1:35	1:26	1:40	1:35	-5	(1:40)	(1:40)
Form, do	Surf temp	4:8	1.5	1.6	5.2	2.7	14.3	2:04	1:49	1:56	2:04	0	(2:00)	1:56
Form, do	do	4:8	1.5	0.7	2.9	2.7	14.3	1:58	1:58	1:50	1:58	0	2:14	1:50
Form, do	do	4:8	1.5	0	0	2.7	14.3	(3:12)	(3:12)	2:36	(3:12)	0	2:36	2:57
Prestressed Concrete Beams													Time to Steel Temperature 750°F Av	
T beam	Rapid defl	10:0	9.0	3.3	9.0	2.0	10.7	1:17	1:21	1:29	1:21	-8	(1:27)	
T beam	Collapse	16:0	14.7	8.0	305.	3.12	16.8	3:40	3:40	3:40	3:40	0	3:26	
T beam	Steel exposed	16:0	14.7	5.+	90.	3.12	16.8	2:35	2:35	2:36	2:35	-1	2:31	
T beam	None	16:0	14.7	5.0	4.6	3.12	16.8	5:37	(6:00)	6:00	(6:00)	(+?)	(6:00)	
Rect sect	Collapse	16:0	9.9	2.6**	34.8**	4.66	24.8	1:56	1:54	1:56	1:56	0	2:00	
Rect sect	do	16:0	9.9	4.9*	36.0*	4.66	24.8	4:39	4:37	4:40	4:39	-1	(4:40)	
Steel Beam - part of floor specimen													1000°F Av	1200°F Max
12I31.8. b	Imminent	13:5 1/2	12.0	0.8	0.64	2.70	14.4	(6:45)	(6:45)	6:53	(6:45)	?	5:29	6:36
8WF17, w	No load fail	12:11 1/2	8.0	2.1	1.04	3.77	20.2	(6:45)	(6:45)	6:45	(6:45)	+?	4:23	5:52
10WF21.5	Imminent	17:4	9.9	4.7	4.2	5.5	29.1	(6:45)	(6:45)	6:47	(6:45)	?	6:08	(6:45)
6I12.5, f	Excess defl	12:10	6.0	6.2	13.1	4.9	26.3	1:57	1:49	2:+	1:57	-3	1:54	(2:15)
6I12.5, f	Exceeded jack extension	12:10	6.0	10.0	127.5	4.9	26.3	1:28	1:25	1:33	1:28	-5	1:24	1:41
6I12.5. f	Structural fail	12:10	6.0	8.6	30.0	4.9	26.3	1:49	1:42	2:01 1/2	1:49	-12	1:56	(2:00)
6I12.5, f	Load fail	12:10	6.0	3.75	12.7	4.9	26.3	(1:58)	(1:58)	1:58	(1:58)	+?	2:04	2:31
6I12.5, f	Imminent fail	12:10	6.0	1.2	5.0	4.9	26.3	(3:12)	(3:12)	3:12	(3:12)	+?	3:11	(4:00)
12WF27. bp	Defl curve shape	17:8	11.95	2.9	1.9	4.7	25.1	3:26	(3:30)	3:00	(3:30)	(+30)	2:19	1:58
12WF27, bp	Defl curve shape	17:8	11.95	3.2	1.0	4.7	25.1	(7:00)	(7:00)	6:30	(7:00)	(+30)	5:26	6:28
12WF27, bp	Defl curve shape	17:8	11.95	2.8	6.2	4.7	25.1	(2:15)	(2:15)	2:15	(2:15)	+?	2:04	1:59

*Within 1 min before collapse. **Cotton waste ignited.

Key to Construction Abbreviations:

b	= bolted to furnace frame	Cell	= cellular steel deck units	GB	= gypsum boards	LP	= lime plaster
bp	= bolted to plates, standard connectors	CF	= concrete fill	GL	= gypsum lath	ML	= metal lath
BR	= built up roof	CS	= concrete slab	GP1	= gypsum plank	PP	= portland cement plaster
s	= continuous over more than one span	f	= freely supported	GP	= gypsum plaster	rect sect	= rectangular section beam
CC	= cellular concrete	Form	= formed steel deck units	GS	= gypsum slab	w	= welded

Figure 2

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