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Proposed Criteria for Defining Load Failure of Beams, Floors, and Roof Constructions During Fire Tests

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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 $L^2/800d$ and an hourly rate of deflection of $L^2/150d$ be taken as an indication of load failure. In these formulas, L is the span between supports of the member or element found to be critical under fire exposure, and d is the distance between upper and lower extreme fibers of the particular structural component or assembly.

1. 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].[1] During initial tests of this study it became apparent that in many cases structural failure might be expected to occur before failure based on a defined temperature rise at 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 a critical deflection[2] of 3 in. [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 I, showed that the corresponding rate of deflection was so great that collapse of the construction might be expected to occur rather promptly.

It appears that a critical deflection method of specifying the time at which failure to carry the load occurs is not 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.

2. Load Failure Criteria

2.1. Deflection

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

2.2. Increase in Rate of Deflection

Tests performed in which heavy steel beams were incorporated as load carrying members showed the shortcomings of deflection alone 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. Therefore, an analysis of some fire endurance data was made to determine the feasibility of using an increase in rate of deflection as an indication of load failure. Figure 1, example II, 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.

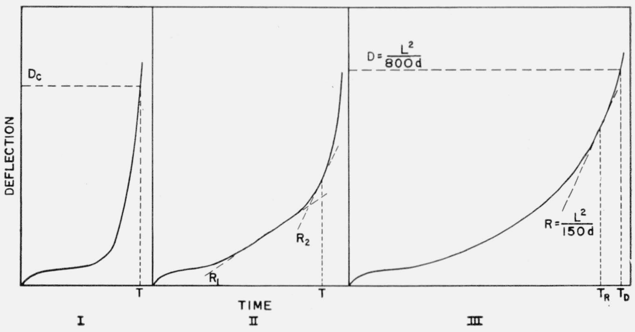

FIGURE 1. *Typical curves of observed deflection data illustrating determination of failure time.*

I, prechosen critical deflection D_c;
II, increase in rate of deflection by predetermined ratio, $R_2=KR_1$;
III, combination of rate and deflection, both determined by size and span of structural element (failure time T_r or T_d, whichever is later).

[1] Figures in brackets indicate the literature references at the end of this paper.
[2] Deflections for determination of load failure are those resulting from fire exposure under design load, in excess of initial deformation due to application of the load.

TABLE 1. *Effect of new criteria on previously determined failure times*

This table compares the times of failures, as determined by the testing personnel on the basis of the criteria listed in the second column, 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 criteria. The criteria define load failure time as the earliest time when a deflection $D=L^2/800d$ and hourly rate of deflection $R=L^2/150d$ have both been attained or surpassed. In these formulas, L=clear span, d=depth to most remote stressed fiber. Most of the data are from tests performed before these formulas 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		Deflection at failure		Criteria		Time criteria reached		Time to failure		Net change of fire endurance	Time to temperature limit rises on unexposed surface	
		L	d	Deflection	Rate	$L^2/800d$	$L^2/150d$	$L^2/800d$	$L^2/150d$	Reported	New criteria		250° F av	325° F max
Floors, wood joist														
		ft:in.	*in.*	*in.*	*in./hr*	*in.*	*in./hr*	*hr:min*	*hr:min*	*hr:min*	*hr:min*	*min*	*hr:min*	*hr:min*
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)
Do	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.+	1,150.+	3.04	16.2	0:26	0:19	0:29½	0:26	−3½	(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
GL, GP	Load failure	12:10	9.75	3	9.+	3.04	16.2	1:43	1:42	1:44	1:43	−1	(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)
Do	do	12:10	10	1.2	30	3.0	16.0	1:44	1:39	1:40	1:44	+4	(1:45)	(1:45)
Do	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)	[b] 2:26
SJ103, GPl, 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
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
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)
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
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, CS, GL, GP	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	(6:45)	(6:45)	4:45	(6:45)	0	4:45	4:53
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
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
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
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)
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
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
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

													Time to steel temperature	
Prestressed concrete beams														
													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)	
Do	Collapse	16:0	14.7	8.0	305	3.12	16.8	3:40	3:40	3:40	3:40	0	3:26	
Do	Steel exposed	16:0	14.7	5.+	90	3.12	16.8	2:35	2:35	2:36	2:35	−1	2:31	
Do	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	[a] 2.6	[a] 34.8	4.66	24.8	1:56	1:54	1:56	1:56	0	2:00	
Do	do	16:0	9.9	[a] 4.9	[a] 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	12.0	0.8	0.64	2.70	14.4	(6:45)	(6:45)	6:53	(6:45)	(?)	6:29	6:36
8WF17, w	do	12:11½	8.0	2.1	1.04	3.77	20.2	(6:45)	(6:45)	6:53	(6:45)	(?)	6:23	5:52
10WF21.5	do	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)
Do	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
Do	Structural fail	12:10	6.0	8.6	30.0	4.9	26.3	1:49	1:42	2:01½	1:49	−12	1:58	(2:00)
Do	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
Do	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)	2:18	1:58
Do	do	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
Do	do	17:8	11.95	2.8	6.2	4.7	25.1	(2:15)	(2:15)	2:15	(2:15)	(+?)	2:04	1:59

[a] Within 1 min before collapse. [b] 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	GPl = gypsum plank	PP = portland cement plaster
c = 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

2.3. 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.

The deflection of a beam or a floor construction in a fire test is the result of several factors, including the deflection due to the flexural stresses produced by the loads, that resulting from changes in temperature, and that resulting from movements of moisture in the materials. Deflections due to shearing deformations usually are small in comparison to those caused by flexure; for our present purpose they will be neglected. The usual assumption will be made that all transverse planes remain plane after bending. Then following the reasoning of Maney [3], it can be shown that the maximum deflection of a beam or floor of constant flexural rigidity throughout its length is given by:

$$y_{\max}=k(L^2/d)\ (e_1-e_2), \tag{1}$$

in which

k = numerical constant; the value of which depends upon the type of support and the methods of loading.

L = length of specimen between supports.

d = depth of specimen (strictly the distance, normal to the neutral plane, between the planes of e_1 and e_2).

e_1-e_2 = algebraic difference between the strains in or near the two surfaces of the specimens, measured in the direction of the span, in planes separated by the distance d.

The equation applies for strains in the elastic range. On examination, it appears that the ratio L^2/d might be useful in expressing limitations on deflection even when plastic deformation occurs. The usefulness of L^2/d for such limitations is demonstrated by study of the data from a number of fire tests. All these tests, which did not include those from reference [1], had been performed, and the time of failure to "sustain the applied load" established, prior to our consideration of the use of the term L^2/d in the criteria for failure. In addition, the tests were selected as representative of constructions which were considered to have failed to sustain the load during the test. Various constants were considered prior to selection of both:

$$\text{a deflection of } D \geq L^2/800d$$

and

$$\text{an hourly deflection rate } R \geq L^2/150d$$

as representing the best fit between the empirically specified load failure time and that predicted in the form of the proposed criteria.

To investigate the effect of applying such criteria for identification of time of load failure of structures during a fire test, data of 50 experiments were analyzed. The results are presented in table 1. 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 or ignition of waste. 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 the defined limiting conditions of ignition of cotton waste or temperature rise due to heat transfer occurred at earlier times than determined by these criteria, such earlier limiting conditions would determine the fire endurance of the specimens. 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 termperature 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 14, and in 23 instances there would either be no change 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.

3. Conclusion

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 under design load will be considered to fail to "sustain the applied load" at that time when both the maximum net deflection resulting from fire exposure has equaled or exceeded $L^2/800d$, and the hourly rate of deflection has equaled or exceeded $L^2/150d$.

In these formulas:

L is the span between supports of the structural component or assembly found critical under fire exposure;

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

D, L, and d are all in the same units of length; R a rate of the same length unit per hour.

Mr. D. E. Parsons suggested the advantages to be gained by use of criteria of the type proposed.

4. References

[1] J. V. Ryan and E. W. Bender, Fire endurance of open-web steel-joist floors with concrete slabs and gypsum ceilings, NBS Building Materials and Structures Report 141 (1954).

[2] Standard methods of fire tests of building construction and materials, ASTM Designation E119, ASTM Standards.

[3] G. A. Maney, Relation between deformation and deflection in reinforced concrete beams, Am. Soc. Testing Materials Proc. 14, II, 310 (1914).

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