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TEN RULES OF FIRE ENDURANCE RATING

BY

T. Z. HARMATHY

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DIX RÈGLES POUR DÉTERMINER LES TAUX DE RÉSISTANCE AU FEU

SOMMAIRE

Les essais d'endurance au feu ne suffisent pas pour obtenir toutes les données dont on a besoin pour évaluer judicieusement les taux de résistance au feu des éléments de construction. Il existe beaucoup trop de modes d'agencement des matériaux pour pouvoir les classer tous au moyen des essais susmentionnés. Heureusement, la théorie des taux de résistance au feu est suffisamment développée pour faciliter l'évaluation de ces taux. L'auteur donne dix règles susceptibles de faciliter l'évaluation des caractéristiques de résistance au feu des éléments de construction lorsqu'on ne dispose pas de données fondées sur des essais d'incendie.

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Ten Rules of Fire Endurance Rating

T. Z. HARMATHY

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National Research Council (Canada)

Fire endurance tests alone cannot supply all the data needed for intelligent appraisal of fire resistant ratings of building elements. There are simply too many different types of assemblies and combinations of materials to classify them all through actual tests. Fortunately, the theory of fire endurance rating is sufficiently advanced to offer guidance in estimating fire endurance ratings. The author sets forth ten rules that may prove useful for quick assessment of the fire endurance of building elements when fire test data on the elements are not available.

IT IS becoming increasingly evident that all the information necessary for classifying building elements from the point of view of their performance in fire cannot be derived from standard fire endurance tests alone. It is hardly conceivable that all various constructions can ever be subjected to fire tests. Even in those cases where test results are available for more or less similar constructions, the classification may not be immediately apparent. It must be clearly understood that certain variations in the dimensions, loading conditions, materials, or workmanship may markedly affect the performance of the individual constructions, and the extent of such a possible effect cannot be evaluated from the fire test report.

The value of the pieces of information obtained from standard fire tests is very limited without a theory that is capable of cementing the pieces into a consistent unit. Fortunately, the theory of fire endurance rating has already advanced far enough not only to offer some guidance in estimating the effect of certain variables on fire endurance but, very often, even to provide rigorous methods of designing building elements for some prescribed performance.

Although the design for fire endurance, whenever possible, is a fairly complex procedure, involving extensive laboratory investigations and sometimes very laborious heat-flow and stress-deflection analyses, it will always prove of extreme value when developing new building products for

maximum economy. In the case of products already on the market, the problem of economy no longer remains, and the question of whether the product will yield a fire endurance higher than some given value may not deserve an extensive theoretical study.

In this report a number of rules will be discussed which may prove useful in the quick appraisal of the fire endurance of building elements. Some of the rules are concerned with the geometry of the construction, some with the materials. All of them are based on experimentally and theoretically well-founded facts. It is hoped that these rules will provide some guidance to those charged with administering building bylaws, and to those who are engaged in either the design or production of building components. Examples are given to illustrate the wide applicability of these rules.

THE TEN RULES

Rule 1: The "thermal" fire endurance of a construction consisting of a number of parallel layers is greater than the sum of the "thermal" fire endurances characteristic of the individual layers when exposed separately to fire.*

This rule is probably the most important aid in assessment of the performance of building elements in fire, and suggests that the result of fire tests conducted on individual components of building elements, e.g., on gypsum board, plywood, brick veneer, plaster on expanded metal lath, etc., with the purpose of determining their "thermal" performance, may also be of considerable value. It is very convenient to use small-scale specimens for these "nonstandard" informative tests.

Because of the difficulties involved in the analytical treatment of the problem of heat flow through composite slabs, it is not possible, at present, to provide proof of this rule. Nevertheless, its validity has been confirmed by the result of several numerical analyses and small-scale fire tests conducted on both combustible and noncombustible constructions.

There is a special case in which the validity of Rule 1 is immediately obvious, i.e., the case of a "quasi-composite" construction consisting of layers made from the same material. It is known (and can be proved by the method described in Reference 1)¹ that by doubling the thickness of a slab, the fire endurance becomes more than twice the original value. Similarly, for a slab of nl thickness (in other words, consisting of n identical layers of thickness l),

$$t_{nl} > nt_l$$

where t is the time of fire endurance and the subscripts denote the thickness of the slabs. This inequality is an expression of Rule 1 for such a "quasi-composite" construction.

*The "thermal" fire endurance is the time at which the average temperature on one side of a construction exceeds its initial value by 250°F when the other side is exposed to a "standard" fire specified by ASTM Method E119.

It may be noted that there are a few cases in which Rule 1 may not be applicable. If, for example, the unexposed surface is covered with a thin, shiny, metal sheet, the radiant heat transfer to the surroundings may become very low due to a decrease in the surface emissivity. Since the insulating value of the sheet is negligible, the fire endurance of the construction might be lower than it would be without the presence of the sheet.

It is also conceivable that the inclusion of a layer which, in itself, exhibits no appreciable fire endurance, but is liable to undergo some chemical reaction accompanied by large exothermic effects at elevated temperatures, will upset the validity of the rule. These are, however, examples not likely to be met in practice.

Rule 2: The fire endurance of a construction does not decrease with the addition of further layers.

This rule is apparently a consequence of the previous rule. Its validity also follows from the fact that, by the addition of further layers, both the resistance to heat flow and the heat capacity of the construction increase, which, in turn, reduce the rate of temperature rise at the unexposed surface.

Although this rule seems quite obvious, a close examination will reveal that it may be subject to certain limitations. Thus, in the light of what has already been noted, it is clear that the addition of a thin metallic layer to the unexposed surface does reduce the fire endurance of the existing construction. Also, since in this rule "fire endurance" is considered in its most general meaning, certain restrictions must be imposed on some properties of the materials to be added, and on the load conditions.

An apparent restriction is that a new layer, if applied to the exposed surface, must not produce additional thermal stresses in the construction, i.e., its thermal expansion characteristics must be similar to those of the adjacent layer. Each new layer must be capable also of contributing to the load-bearing capacity of the construction at least as much as is required to carry the increased dead load. If this requirement is not fulfilled, the allowable live load must be reduced by an amount equal to the weight of the new layer. Because of these limitations, this rule should not be applied without due criticism.

Rule 3: The fire endurance of constructions containing continuous air gaps or cavities is greater than the fire endurance of similar constructions of the same weight, but containing no air gaps or cavities.

The validity of this rule rests on the fact that by providing for voids in a construction, additional resistances are produced in the path of heat flow. Numerical heat flow analyses indicated that a 10 to 15 per cent increase in fire endurance can be achieved by creating an air gap at the mid-plane of a brick wall.² Since the gross volume of constructions is also increased by the presence of voids, the air gaps and cavities have a beneficial effect on the stability as well. However, constructions containing com-

bustible materials within an air gap may be regarded as exceptions to this rule because of the possible development of burning in the gap.

Rule 4: The farther an air gap or cavity is located from the exposed surface, the more beneficial is its effect on the fire endurance.

In the heat transfer through an air gap or cavity, radiation is the predominant mechanism. Since heat transfer by radiation increases markedly with the average level of temperature in the void, an air gap or cavity is a very poor insulator if it is located in a region which attains high temperatures during fire exposure.

Rule 5: The fire endurance of a construction cannot be increased by increasing the thickness of a completely enclosed air layer.

There is evidence² that if the thickness of the air layer is larger than about $\frac{1}{2}$ in., the heat transfer through the air layer depends only on the temperature of the bounding surfaces, and is practically independent of the distance between them. (This rule is not applicable if the air layer is not completely enclosed, i.e., if there is a possibility of fresh air entering the gap at an appreciable rate.)

Rule 6: Layers of materials of low thermal conductivity are better utilized on that side of the construction on which fire is more likely to happen.

The validity of this rule has been demonstrated.² The rule may not be applicable to materials undergoing physico-chemical changes accompanied by significant heat absorption or heat evolution.

Rule 7: The fire endurance of asymmetrical constructions depends on the direction of heat flow.

This rule is a consequence of Rules 4 and 6, which point out the importance of the location of air gaps or cavities and of the sequence of different layers of solids.

Rule 8: The presence of moisture, if it does not result in explosive spalling, increases the fire endurance.

The flow of heat through the construction is greatly hindered by the absorption of the heat associated with moisture desorption. It has been shown^{2,3} that the gain in fire endurance may be as high as 8 per cent for each per cent (by volume) of moisture in the construction. As the latent heat required for the desorption of moisture is roughly proportional to the amount of moisture present in a unit volume of the material, there is no direct relationship between the relative humidity (in the pores) of the material and increase in fire endurance.

As pointed out by Shorter and Harmathy,⁴ and Harmathy,³ materials of low permeability (dense concretes) are liable to undergo explosive spalling if the moisture content is higher than a critical value. The permeability of mature portland cement pastes is several orders of magnitude lower than that of fresh pastes; thus with aging, concretes become more vulnerable to spalling.

Figure 1. Elements of a floor construction.

Rule 9: Load-supporting elements, such as beams, girders, and joists, yield higher fire endurance when subjected to fire endurance tests as parts of floor, roof, or ceiling assemblies than they would when tested separately.

Before being able to prove the validity of this rule it is necessary to define the meaning of a few terms. Figure 1 is a diagrammatic picture of a common floor construction. From the point of view of their role in transferring the load to some vertical bearing construction (wall or column), the elements of this floor can be divided into three groups. The upper layer can be termed the "load-receiving" element. This layer is supported at short spans, therefore it is generally a light construction. The components of the second layer can be called "load-transmitting" elements. As they are bridging somewhat larger spans, they usually contain some steel reinforcement. The components that span the whole distance between two walls or columns can be termed "load-supporting" elements. These are either entirely of steel (trusses, girders, beams, joists), or are heavily reinforced with steel. Finally, the walls or columns to which all the load imposed on the floor is last transferred, can be termed "load-bearing" elements. It may be noted that very often a single layer plays the part of both the "load-receiving" and "load-transmitting" elements. The illustration at left in Figure 2, shows how, under the conditions contemplated by the design, the various elements contribute to transferring the load to the ground.

During the fire test the supporting elements are, as a rule, under the most adverse temperature conditions, and since they are spanning the largest distances, their deflection becomes significant at a stage when the strength of the transmitting and receiving elements is hardly affected by the heat. These elements will, of course, follow the deflection of the sup-

Figure 2. "Load flow" diagrams.

porting elements, but as a result of their elastic bending, an increasingly larger portion of the load will be switched directly to the bearing elements (walls, columns). Thus the load carried by the supporting elements will gradually decrease. The illustration at right in Figure 2 shows how the "load flow diagram" may appear toward the end of the fire test.

When load-supporting elements are tested separately, the imposed load is constant and equal to the design load throughout the test. Under such circumstances they cannot yield higher fire endurance than they do when tested as parts of a floor, roof, or ceiling assembly.

Rule 10: The load-supporting elements (beams, girders, joists, etc.) of a floor, roof, or ceiling assembly can be replaced by such other load-supporting elements which, when tested separately, yielded fire endurances not less than that of the assembly.

The validity of this rule rests on Rule 9. A beam or girder, if capable of yielding a certain performance when tested separately, will obviously yield an equally good or better performance when it forms a part of a floor, roof, or ceiling assembly. It must be emphasized that the supporting element of one assembly must not be replaced by the supporting element of another assembly if the performance of this latter element is not known from a separate (beam) test. Because of the load-reducing effect of the receiving and transmitting elements, from the result of a test performed on an assembly, the performance of the supporting element (beam, etc.) alone cannot be evaluated by simple arithmetic. This rule clearly indicates the advantage of performing fire tests on supporting elements separately and proves the validity of the concept that the results are more widely applicable if smaller units rather than complex assemblies are subjected to fire tests.

Figure 3 is a diagrammatic illustration of the rules discussed in this paper. Although these rules do not eliminate the need for accurate and elaborate design methods, they may give some assistance in solving many problems encountered in everyday practice.

Figure 3. Diagrammatic illustration of ten rules.

t = fire endurance

A number of examples that show how the rules can be applied to practical cases follow:

APPLICATION OF THE RULES

EXAMPLE 1: A contractor would like to use a partition consisting of a $3\frac{3}{4}$ -in.-thick layer of red clay brick, a $1\frac{1}{4}$ -in.-thick layer of plywood and a $\frac{5}{8}$ -in. gypsum wallboard, at a location where 2-hr fire endurance is required.

Question: Is this assembly capable of providing 2-hr protection?

Answer: Yes. The fire endurance of a $3\frac{3}{4}$ -in.-thick brick wall is approximately 80 min. In small-scale experiments the fire endurance of a $1\frac{1}{4}$ -in.-thick plywood was found to be 30 min, and that of a $\frac{5}{8}$ -in. gypsum wallboard 13 min. According to Rule 1, the fire endurance of the assembly must be larger than $80 + 30 + 13 = 123$ min.

EXAMPLE 2: A manufacturer of roof slabs would like to obtain experimental evidence that his products are capable of yielding 2-hr fire en-

durance. According to a rigorous interpretation of ASTM E119,* however, only roof assemblies, including the roof slabs as well as the cover and the supporting elements, can be subjected to fire tests, and therefore a fire endurance classification cannot be issued for the slabs separately. The manufacturer thinks, however, that his slabs will yield 2-hr fire endurance even without the cover, and any beam of at least 2-hr fire endurance may serve as satisfactory support. Thus, he believes that by prescribing a particular cover and supporting system to be used with the slabs, the sale of his product will suffer.

Question: Is it possible for the manufacturer to obtain classification for the slabs separately?

Answer: Yes. According to Rule 10 it is not contrary to common sense to test and classify roofs and supporting elements separately. Furthermore, according to Rule 2, if the roof slabs actually yield a 2-hr fire endurance, the endurance of an assembly including the slabs cannot be less than 2 hrs either. The recommended procedure is to assemble the roof slabs on any convenient supporting system (not regarded as part of the specimen) and to subject them to a load which, besides the usually required superimposed load, includes some allowance for the weight of the cover.

EXAMPLE 3: The fire endurance of a floor construction containing simple steel floor units was found to be 2 hrs and 40 min.

Question: Is there any hope that by replacing the simple floor units by cellular units the fire endurance can be increased to 3 hrs?

Answer: According to Rule 3 this replacement will favorably affect the performance of the construction, but there is no simple way of estimating the actual gain in fire endurance.

EXAMPLE 4: A steel-joisted floor and ceiling assembly is known to have yielded a fire endurance of 1 hr and 35 min. At a certain location 2-hr endurance is required.

Question: What is the most economical way of increasing its fire endurance by at least 25 min?

Answer: A thorough examination of the drawings would be necessary. Slightly increasing the thickness of the ceiling plaster is always very effective. In this way there will be a twofold gain in fire endurance:

- (i) a gain due to the greater thickness of plaster, and
- (ii) a gain due to shifting the air gap farther from the exposed surface (Rule 4).

EXAMPLE 5: The fire endurance of a particular brick cavity wall consisting of two 3¾-in.-thick layers separated by a 2-in. air gap, is 4 hrs 40 min.

*The text of ASTM E119 is similar to that of NFPA No. 251, Standard Methods of Fire Tests of Building Construction and Materials.

Question: Can the fire endurance of the wall be extended to 5 hrs by increasing the thickness of the air gap to 4 in?

Answer: No, by virtue of Rule 5.

EXAMPLE 6: In order to increase the insulating value of its precast roof slabs, a company has decided to make the slabs from two layers of different concretes. The lower half of the slabs, where the strength of the concrete is immaterial (since all the tensile load is carried by the steel reinforcement), is now made from a concrete of low strength but good insulating value. For the upper layer, where the concrete is supposed to carry the compressive load, the original high strength, high thermal conductivity concrete has been retained.

Question: How will the fire endurance of the slabs be affected by the change?

Answer: The effect on the thermal fire endurance is beneficial for two reasons:

(i) the total resistance to heat flow of the new slabs has been increased due to the replacement of a layer of high thermal conductivity by one of low conductivity, and

(ii) the layer of low conductivity is on the side to be exposed to fire, where it is more effectively utilized according to Rule 6. The change is also beneficial to resistance of the slabs against collapse. The layer of low thermal conductivity provides a better protection for the steel reinforcement, therefore the time of attaining the temperature at which the creep of steel becomes significant will be extended.

EXAMPLE 7: The fire endurance of an exterior wall consisting of a 3¾-in. layer of brick and a 3¾-in. layer of sandstone is known. The wall was tested with the brick layer exposed to the fire.

Question: Can the result be applied to the case when the sandstone is to be exposed to fire?

Answer: No, by virtue of Rule 7. From Rule 6 it is evident that the construction will yield a lower fire endurance when tested from the direction of sandstone. (The thermal conductivity of sandstone is higher than that of the brick.)

EXAMPLE 8: A floor construction with concrete on steel floor units was tested in 1956 and was found to give 3 hrs and 18 min fire endurance. The test report reveals that the age of the specimen was 35 days on the day of the test. There is no information available concerning the moisture content of the concrete slab.

Question: Would the fire endurance of this construction be higher or lower if the test were repeated with the observance of the 1958 revision of ASTM E119?

Answer: Probably it would be lower. According to ASTM E119-58, the

construction shall not be tested until the dampest section of the assembly attains a 70 per cent relative humidity. It is the experience of this laboratory that this humidity level cannot be attained in 35 days. It is also known⁵ that the sorption curve of concretes is very steep in the 80 to 100 per cent relative humidity range; in other words, above 80 per cent a small change in relative humidity may mean a significant difference in the amount of adsorbed moisture, and thus, in accordance with Rule 8, a significant difference in the fire endurance.

EXAMPLE 9: In a test of a floor assembly the deck failed thermally at 2 hrs and 21 min. The submitter asked the testing authorities to continue the test to see whether the beam would be capable of sustaining the applied load for a 3-hr period. The construction collapsed at 3 hrs and 15 min.

Question: Can the beam be qualified as one of 3-hr fire endurance?

Answer: No. According to Rule 9 the beam was not tested under the most adverse conditions. It is possible that in combination with another deck, which exhibits less rigidity and contributes in a lesser degree to supporting the load, the same beam will yield a considerably poorer fire endurance. It is obvious from Rule 10 that if a beam is intended to be used in conjunction with a variety of floor or roof constructions, the best policy is to subject it to a separate fire test.

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