REVIEW ON THE REQUIREMENTS ON FIRE RESISTING CONSTRUCTION

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ABSTRACT

Buildings with new architectural features might have difficulties in complying with the prescriptive fire codes in Hong Kong. Obvious examples are the complex and large-scale buildings. Engineering performance-based fire codes (EPBFC) should be an effective alternative and a study on how to implement EPBFC in Hong Kong has been carried out at The Hong Kong Polytechnic University since 1995. The first area of study identified is on the fire safety objectives since there are no clear objectives stated in the existing codes. As EPBFC is very complicated, a long-term in-depth research for coming up with a performance-based fire code is required. In places like USA, UK and Japan, years of study were required to develop workable EPBFC. But there are still rooms for further modifications and introduction of new evaluating tools. Full-scale burning tests should be carried out where necessary.

In this connection, one of the streams of fire safety provisions, the fire resisting construction, will be studied to investigate what should be done for the implementation of EPBFC for fire resisting construction. The current requirements in the local code on fire resisting construction for buildings are reviewed first. The development of fire resistance period (FRP) requirements is described with the factors affecting FRP reviewed. Standard fire tests for assessing FRP of the elements of construction are reviewed and briefly compared. Further studies on FRP requirements for buildings unable to comply with the prescriptive code are strongly desirable. This is particularly important for evaluating engineering performance-based fire codes.

1. INTRODUCTION

Many new architectural features have been introduced to cope with the speedy development of building construction. However, some of them are not able to comply with the prescriptive fire codes [e.g. 1-3] as they may not be up-to-date for the newly developed technologies and materials. Engineering performance-based fire codes are therefore considered to implement. However, it is found that fire safety objectives in prescriptive codes are not clearly described. It seems not feasible to have something "concrete" worked out within five years. For example, even discussing the Karaoke Establishments Bill [4] took more than 4 years!

How long a structure can stand a fire without collapsing is one of the main concerns in providing safety under accidents, though the "911 incident" with total collapse of the World Trade Center in New York [5] had raised the concern on potential risk of terrorist attack fire as well. Basically, there are accidental fires, arson fires, terrorist attack fires and natural disaster fires. Fire safety provisions are basically for accidental fires. At the moment, though there are sound tendencies moving towards protection against fires other than accidental ones for some buildings with special features or representing the country. Anyway, providing protection against arson fires or terrorist attack fires is a "security" problem and would cost lots.

In the local code for fire resisting construction [1], buildings are required to be broken down into smaller compartments or to have adequate fire resistance period (FRP) for preventing the spread of smoke and flame and ensuring the stability, insulation and integrity of the structural elements.

In passive building design, FRP requirements are different for different intended uses of buildings with the specified compartment volume. All the elements of construction, such as walls, floors, beams and columns, should follow the requirements for their building types. The Code of Practice for Fire Resisting Construction 1996 (FRC code) [1] published by Buildings Department (BD), and Part XV of the Building (Construction) Regulations [6] described the need for fire resisting construction. The former statutory instrument is the practical guide for compliance with the requirement. This is the latest edition of the FRC code since 1989 with revisions made in between. Elements of construction should be examined by British Standard BS 476: Parts 20-22: 1987 [7-9] as stated in the definition of FRP in local code [1]:

The period of time for which any element of construction, wall, fixed light, door, fire shutter or other component of a building is capable of resisting the action of fire when tested in accordance with BS 476: Parts 20 to 22: 1987 or as specified in tables A to F in the local Code.

In the standard fire tests, three criteria are to be examined, including loadbearing capacity, integrity and insulation. The definitions of those terms appeared in BS 476: Part 20:1987 and will not be repeated here.

Basically, loadbearing capacity of the structural elements is the ability to resist the applied loading without collapsing; integrity is the ability to prevent flame from spreading to adjacent compartments and insulation is to keep the temperature rise on the unexposed side controlled. The FRP in local code is specified in hours; 1-hour, 2-hour and 4-hour are common grades in Hong Kong premises. Reasons for selecting those values will be discussed later in this paper. But before doing so, rationale behind which should be fully understood so that safe enough buildings can be constructed.

In this paper, development of FRP requirements is reviewed first. Factors affecting FRP are then analysed. The prescriptive codes of FRP in the United Kingdom (UK) and Hong Kong are discussed. The standard fire tests, determining the performance of the structural elements and their FRP, are significant for building safety. Results will be useful for understanding what should be assessed in implementing engineering performance-based fire code for fire resisting construction; and implementing “engineering approach” for those buildings with new architectural features having difficulties in complying with the FRC code.

2. EVOLUTION OF FIRE RESISTING CONSTRUCTION

Hong Kong was under British administration before smooth reunification to China in July 1997. Most of the policies and ordinances had made reference to those in UK. Therefore, reviewing the development of fire safety control in UK would be helpful in understanding the local fire codes. Codes related to structural fire protection in UK were developed as follows [e.g. 10-13].

- 17th Century

Development of legislation for fire safety in UK has to be traced back to 300 years ago [10,11]. In the 17th century, there was no statutory instrument until the big conflagration Great Fire of London, lasting for 4 days and destroyed 80 % of the city, in 1666 [12]. Before that, there was little concern on the potential fire hazard. The dwellings for the poor were erected by combustible timber while those for the rich were brick-built with brick chimney. The city was not in well urban planning that the houses were closely spaced, with overhangs almost touching those of the opposite sides. These were the causes leading to the serious historical disaster in London. In the following year after that, the King issued a Royal Proclamation concerning the building materials, the width of streets and the construction of new buildings, starting large-scale fire precautions in the city. Other cities in UK followed suit. Two pragmatic regulations established had become the foundation of fire protection principles including fire resisting construction and fire containment in the future. They are:

- The external walls have to be constructed of brick or stone.
- The thickness of the brick or stone walls is related to the height of the building.

Since then, more attention was paid to fire protection.

- 18th Century

Timber-built housing was prohibited. Brick was a substitution of the universal building material [10,11]. In 1774, Fire Prevention (Metropolis) Act was passed. Buildings were classified into seven types with designated thickness of walls and the exposed timber had to be covered by non-combustible materials. Permissible materials for construction of roofs and walls were also laid down in the Act. A committee, the predecessor of Royal Institution of British Architects (RIBA), formed by architects in 1791 started to develop fire tests in which the fire development in an enclosed room was investigated. It was followed by some advancement in fire protection. However, they took into effect in the practical world in the next century.

- 19th Century

“Fire proof” floors were prescribed in the building regulations since the early 19th century. Meanwhile, other fire-fighting systems were developing as well. In the 1844 Metropolitan Building Act, the building classes were contracted from seven to three, namely dwelling houses, warehouses and public buildings. The maximum volume of warehouses was 200,000 ft^3 and elements of construction of public buildings were required to be ‘fire-proof’. Concrete was introduced into all public buildings with iron and steel in 1860s. London became the pioneer among the world on the issue of fire protection for the time being, with its legislation prescribing all the major construction elements should be of non-combustible materials and the buildings should be fire resisting.

The legislation was amended in the 1894 London Building Act which constituted some new sessions concerning fire safety, including 250,000 ft^3 to be the maximum volume for warehouses; 80 ft to be the maximum height for any building; and public buildings with cubical extent exceeding 125,000 ft^3 be fire-resisting construction in order to provide at least half an hour for occupants' evacuation and fire fighting by the fire brigade.

The British Fire Protection Committee (BFPC) was founded [13] in the following year and being the foremost in standardizing fire-testing techniques. Their work became the foundation of the present-day fire resistance tests and their 25-year effort led to the establishment of fire tests using furnaces.

- 20th Century

The revised London Building Acts (Amendment) Act 1905 constituted a new schedule of fire-resisting materials, apart from the requirement of means of escape. Building designers then integrated means of escape into their design with the elements of construction being made of fire-resisting materials. Legislations elsewhere in UK were also amended to follow it.

Following the BFPC, the British Engineering Standards Association, the preceding organization of the British Standards Institution (BSI), carried out the fire tests for non-combustibility, non-flammability and fire resistance in considering the previous work of the BFPC and the other countries. The significant document BS 476: 1932 Fire Tests on Building Materials and Structures [14], which is still affecting the building construction in Hong Kong and UK at the moment, was issued. But the British Standard for fire resistance was not appeared until the Model By-laws in 1952 [13].

A Joint Committee collaborated by the Building Research Board and the Fire Offices' Committee in 1938 had published significant reports, the Fire Grading of Buildings [15,16], after the war in 1946 regarding the fire precautions in buildings since the enemy attack in the war had made disastrous damage. The post-war reports gave detailed recommendations on the general principles and structural precautions (Part I), fire fighting equipment, personal safety and chimneys and flues (Part II). Part I will be discussed in the later session, with new interpretation on the building grades. Most of the current regulations are influenced by the Reports.

The Model By-laws for England and Wales were revised in 1952, taken into consideration the recommendations in Fire Grading of Buildings Part I. Simultaneously, Inner London made its own London Building (Constructional) By-laws 1952. Both of them were the principal by-laws in their regions. Some new requirements for fire resistance of buildings were stated, for example, specified fire resistance periods should be provided for the elements of construction.

However, in 1961, the Public Health Act empowered the newly established building regulations to replace the 1400 sets of model by-laws used throughout England and Wales, while the London Building By-laws with some amendments were still effectual within Inner London. The first Building Regulations was enacted in 1965 throughout England and Wales with several revisions made up till now. There were no requirements for means of escape until the enactment of Fire Precautions Act 1971, which was also applied in London since the London Building (Constructional) By-laws were mainly in connection with the fire resistance and the materials of elements of construction.

In 1984, a new set of approved documents was published so as to simplify the complex regulatory systems establishment before and provide practical guidance to the compliance with regulations. For fire safety, Approved Document B illustrated the technical requirements for means of escape, fire resisting construction and the fire services system as well.

3. FIRE GRADING OF BUILDINGS

Fire Grading of Buildings [15], published by a joint committee of the Building Research Board of the Department of Scientific and Industrial Research and the Fire Offices' Committee in 1946, is the most significant study on the development of fire resisting construction in this century. This post-war building study mainly focused on the reconstruction of the damaged houses and new buildings after the war.

Fire hazards are divided into 3 subdivisions, namely personal hazard, damage hazard and exposure hazard, in this report. Personal hazard concerns about the safety of life, while damage hazard concerns about the property and exposure hazard deals with the surrounding buildings.

Fire resistance period was developed from damage hazard which was the basis to classify different occupancies. Fire load was used to measure the damage hazard quantitatively. The total weight of combustible material was not used because different materials may exhibit different combustibility. More combustible materials are not necessarily equal to higher potential hazard. In the building study, fire load (B.Th.U's./sq.ft.) is given by multiplying the weight of all combustible materials by their calorific values and dividing by the floor area. It should be noted that 1 B.Th.U's./sq.ft. is equal to 11.35 kJm^{-2}.

After defining the fire load, the means to grade the occupancies, the committee investigated the common occupancies in and outside the country. Some reliable data relating to the fire load of several types of occupancies were obtained. They are summarized as follows:

For residential buildings, hotels, hospitals, schools, offices and similar occupancies, the fire loads usually do not exceed 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}); for shops and factories, their fire loads exceed 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}); and for warehouses, the fire load can be up to 1,000,000 B.Th.U's./sq.ft. (or 11,350 MJm^{-2}). In respect to the data, the committee proposed a grading method for the occupancies:

- Low Fire Load: fire load not more than 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}).
- Moderate Fire Load: fire load more than 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}) but less than 200,000 B.Th.U's./sq.ft. (or 2,270 MJm^{-2}).
- High Fire Load: fire load more than 200,000 B.Th.U's./sq.ft. (or 2,270 MJm^{-2}) but less than 400,000 B.Th.U's./sq.ft. (or 4,540 MJm^{-2}).

These are also shown in Table 1.

The relation between the temperature and duration of a fire and various fire loads was first investigated in America. Matching with the curves of standard test, the equivalent severity of the building fire (expressed in hours) was then assessed. Since the standard American time-temperature curve is coincident with that of British Standard, the fire severities of different fire loads can also be applied in UK. Low, moderate and high fire load categories are found to match the fire severities of 1, 2 and 4 hours, as shown in Table 2.

From the above assumption, the committee concluded that in an attempt to resist a complete burn-out without collapse, a building of low fire load should require an FRP of 1 hour in its elements of structure. Likewise, a 2-hour FRP is required for buildings of moderate fire load and a 4-hour FRP is required for buildings of high fire load to resist the complete burn-out without failure in structure, which is called "fully protected construction", as shown in Table 2.

For convenience, types of construction, designated for different periods of fire resistance and fire protection to the buildings, are classified in the report. Types 1, 2 and 3 constructions are designated for buildings of fully protected construction with elements of structure having not less than 4 hours, 2 hours and 1 hour of FRP respectively, as shown in Table 3. The remaining Types 4 to 7 constructions are those not capable of resisting a complete burn-out; not having specified fire resistance or having some elements of combustible materials.

After the types of construction have been defined, the required FRP for structural elements of each type are specified. Separating walls, which are used to separate different buildings, should have an FRP of 4 hours in all cases regardless of the types of construction, since the occupancies on each side of the wall would vary with time. Division walls, which separate parts within a building, can follow the types of construction they are situated. In this respect, a 4-hour FRP is deserved for Type 1 construction; 2-hour FRP for Type 2 and 1-hour FRP for Type 3, however, after justification, an FRP of 2 hours should be provided in order to ensure fire safety. For the external walls, they also follow the types of construction. But 2-hour FRP should be provided for those buildings exceeding 50 ft in height. Classification of walls is illustrated in Fig. 1. All columns and beams are awarded an FRP of that required in the walls they are supporting. The required fire resistance period of floors and roofs for Types 1, 2 and 3 construction are 4 hours, 2 hours and 1 hour respectively. As basements impose specially high risk owing to the absence of openings for escape of smoke of high fire load storage, higher grade of fire resistance should be adopted. A minimum of 2 hours FRP should be provided for buildings of low fire load, and 4 hours FRP for moderate fire load. Sufficient fire safety measures should be provided with 4-hour FRP in the high risk basements in this respect. Details are shown in Table 4.

Table 1: Classification of fire load (FL) in Fire Grading Report [15]

FL (B.Th.U's./sq.ft.)	FL (MJm^{-2})	Classification of Fire Load	Example Buildings
FL ≤ 100,000	FL ≤ 1,135	Low	Domestic buildings, hotels and offices
100,000 < FL ≤ 200,000	1,135 < FL ≤ 2,270	Moderate	Trade and factory buildings
200,000 < FL ≤ 400,000	2,270 < FL ≤ 4,540	High	Bulk storage buildings

Table 2: Relationship among fire load, equivalent severity and FRP of fully protected construction [15]

Classification of fire load	Equivalent severity (hours)	FRP (hours)
Low	1	1
Moderate	2	2
High	4	4

Table 3: Types of construction vs FRP [15]

Types of construction	FRP (hours)
1	≥ 4
2	≥ 2
3	≥ 1

Table 4: Minimum fire resistance (in hours) requirement in Fire Grading of Buildings [15]

Elements of construction		Types of construction		
		Type 1	Type 2	Type 3
Wall and beam and columns supporting wall	Separating wall	4	4	4
	Division wall	4	2	2
	External wall	4	2	2, 1*
Floor		4	2	1
Roof		4	2	1
Basement		4	4	2

* 1-hour FRP is for buildings not higher than 50 ft.

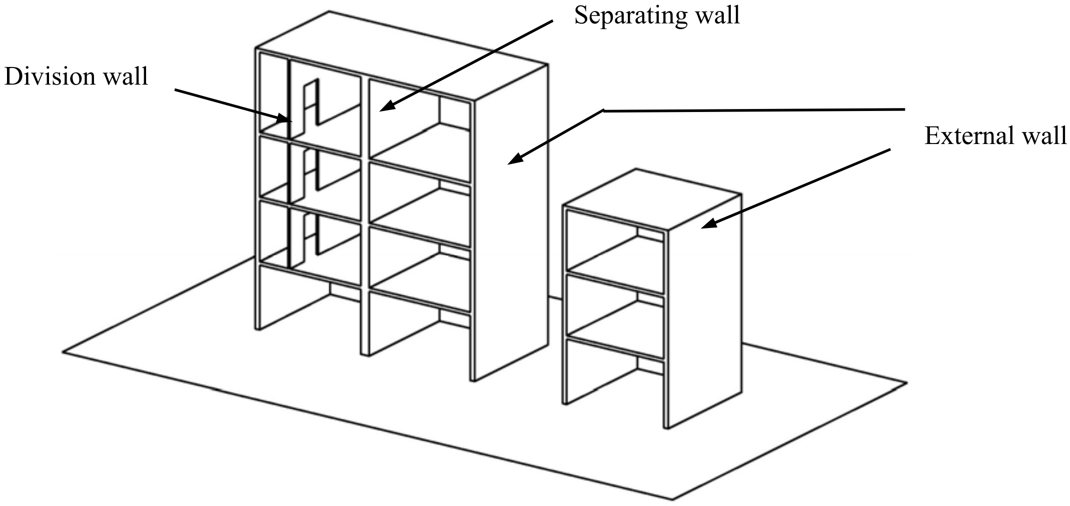

Fig. 1: Separating wall, division wall and external wall

4. FRP IN A COMPARTMENT

As discussed in the Fire Grading Report, FRP requirements were only based on the fire load, that implied equal fire loads would give identical fire severities. But some of the researches on fire growth showed that fire load is not the only factor which affects the fire severity [13].

In the later studies, it was discovered that the severities of fires can vary in a wide range even if they are of equal amount of fire load. Different materials of the same weight and the same calorific value may still have distinctive fire risks, since they may differ in their ease of ignition and burning rate [15].

The ventilation available, determined by the dimensions of the openings, would influence the development and the temperature of the fire, since sufficient air supply and amount of fuel may lead to flashover, which is an uncontrollable fire stage.

Enclosures with high heat capacity may absorb excessive heat generated and so the temperature of the fire can be kept under control. It might also avoid ignition of some of the other contents inside the compartment.

Fire load in dwellings may be higher than that in hotels, but the occupancy level is comparatively lower and their occupants are more familiar with the environment. Therefore, it is not appropriate to regard dwellings as having higher fire hazard than hotels. From this example, it revealed that the fire severity is affected by a number of factors.

The air supply through the openings for the combustion process and the thermal properties of the enclosures would affect the temperature reached while the quantity of fuel would control the duration of combustion. The occupants' familiarity with the environment and the occupancy level are also the determinants of the requirements of FRP [13].

The required FRP denoted by t_f (in minutes) in a compartment can be expressed in terms of the total fire load L (in kg - equivalent of wood); floor area A_F (in m^2); area of window openings A_w (in m^2) and area of internal surfaces to which heat is lost excluding windows A_T (in m^2) [17]:

$$t_f = \frac{L}{(A_w A_T)^{1/2}} \tag{1}$$

which can be written as:

$$t_f = \frac{L}{A_F} \frac{A_F}{(A_w A_T)^{1/2}} \tag{2}$$

The term L/A_F denotes the fire load density, which was perceived as the unique parameter for determining FRP. The significance of ventilation and compartment size and shape is revealed exhaustively by the term $A_F/(A_w A_T)^{1/2}$.

However, the thermal properties of the envelope materials were not included in the above correlation. Studies on fully-developed fire in a compartment have shown that heat generated by combustion might be transferred to the internal surfaces, including walls, floors and ceiling. Later on, this factor has also been taken into account in the evaluation of equivalent fire resistance t_e by adjusting the "ventilation factor" as well as fire load density [18] in terms of the total internal surface area of the compartment A_t, height of the window opening H and q_f:

$$t_e = 0.067 q_f \left(\frac{A_t}{A_w \sqrt{H}} \right)^{1/2} \tag{3}$$

Rewriting the above for q_f expressed as a density L/A_t:

$$t_e = 0.067 \frac{L}{\left(A_t A_w \sqrt{H} \right)^{1/2}} \tag{4}$$

The equivalent fire resistance for a compartment can be evaluated provided that the fire load, dimensions of the compartment and window openings are known. The structural elements of the compartment encountering the same severity would follow the FRP required in that compartment.

In practice, the required FRP for structural elements are specified according to the usages/occupancies of the compartments [19]. In Hong Kong, it would be upgraded if the compartment volume exceeds the specified value of 28,000 m^3 [1]. The classification of FRP by building usages was given by the historical development, such as in Fire Grading of Buildings.

5. STANDARD TESTS FOR FIRE RESISTANCE

The FRP of structural elements in local premises are required to be examined by British Standard fire tests [7-9] as specified in the local FRC code. In light of this, it is valuable to study these standard fire tests to understand how the FRP is labeled onto the various elements of construction. The constraints of the tests may also be figured out to appraise their accuracies.

The full-scale testing is more desirable in general terms since it can offer higher accuracy without the errors created by uncertainty parameters of the scaling-down conditions. In the standard tests, the test specimen is to be accommodated in a furnace with fixed size, so that the scale of the test specimen is dependent on whether it can be placed inside the furnace. Too large a test construction will be scaled down to a specified size as described in the standards [7-9]. Heating and pressure will be applied onto the test specimen inside the furnace, as in Fig. 2. Thermocouples are used to measure the temperature of the internal environment of the furnace. The heating conditions will be controlled by limiting the input rate of fuel to follow the standard temperature/time curve which can be expressed in terms of the mean furnace temperature above the initial furnace temperature (taken as 20 °C) T (in °C) and the heating time t (in minutes):

$$T = 345 \log_{10}(8t + 1) + 20 \quad (5)$$

Three performance criteria, including loadbearing capacity, integrity and insulation, are used to examine the fire resistance of structural elements. The details of them are clearly stated in the standard. Heat will be applied until failure presented in any one of the criteria. The required FRP for that construction is taken from the heating time.

Different nations have their own system of standard tests. Those in UK, USA, Japan, Germany and International Organization for Standardization are briefly reviewed and compared. The standard test methods of interest are as follows:

- British Standard BS 476: Parts 20-22: 1987 [7-9]
- International Organization for Standardization ISO 834: 1999 [20]
- American Society for Testing & Materials ASTM E119: 2000 [21]
- Japanese Industrial Standard JIS A 1304: 1994 [22]
- Deutsches Institut Fur Normung DIN 4102: Part 2: 1977 [23]

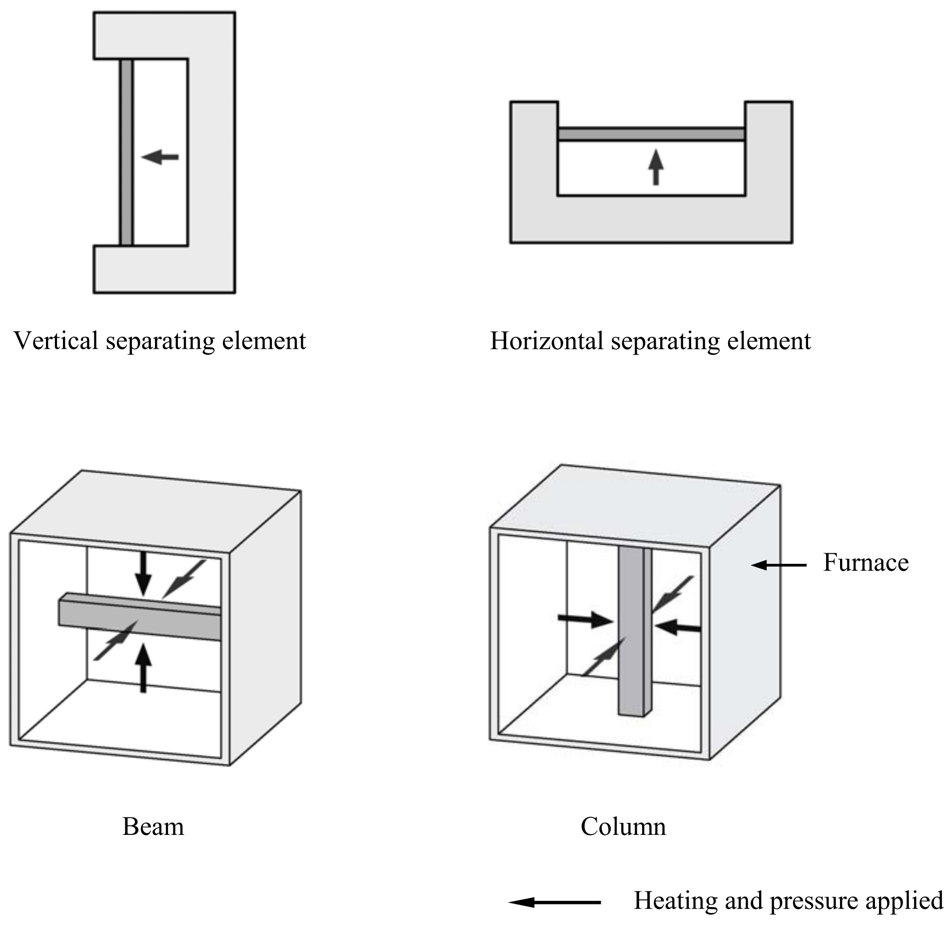

Fig. 2: Heating and pressure applied on test specimen in BS 476

Their approach to assess the fire resistance of constructions are identical and similarity is shown in the curves, as in Fig. 3. However, they are slightly diverted in the following areas:

- Size of test specimen
- How the specimen is heated
- Standard temperature/ time curve
- Test methods
- Performance criteria

They are summarised in Table 5.

It should be noted that new British Standards for fire resistance tests are going to replace the BS 476: Parts 20 to 24. In order to standardize the different tests across the European Union (EU) countries, European Commission has created a new system harmonising the existing national tests among the EU countries [24]. The BS EN 1363 to 1366 and 1634-1 are the new European Standards (ENs) adopted as British Standards. Standards in other EU countries, such as France, German, will have the same operation. A new classification of fire resistance and performance criteria will be generated shortly as an European Standard. Those existing standard tests in conflicting with the new system will be withdrawn.

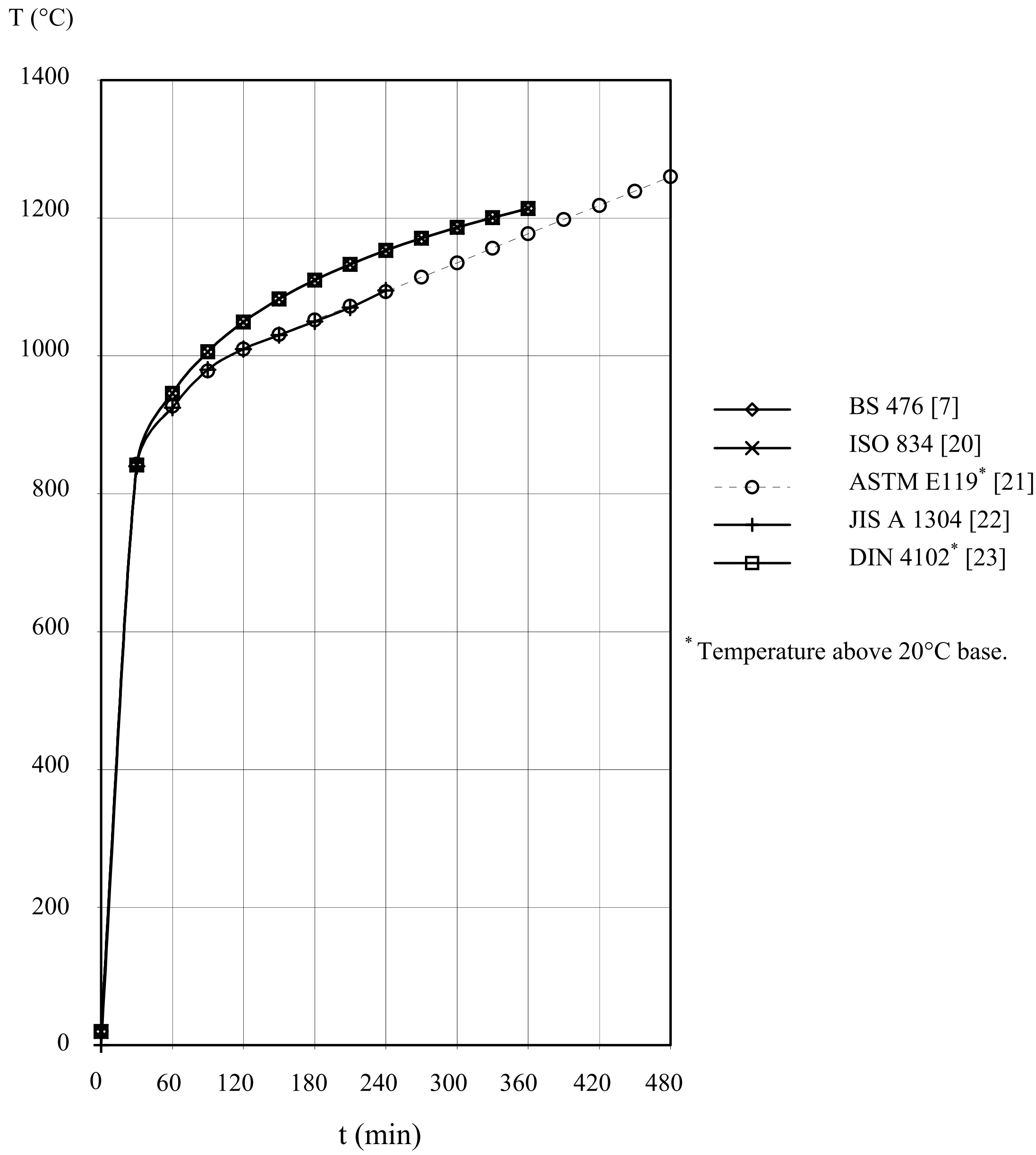

Fig. 3: Comparison of different standard temperature/time curves

Table 5: Differences in other fire tests for building materials from BS 476

Tests	BS 476 [7]	ISO 834 [20]	ASTM E119 [21]	JIS A 1304 [22]	DIN 4102 [23]
Size of test specimen	Full size if applicable, otherwise, provide at least the minimum size prescribed.	As in BS 476.	Full size if applicable, otherwise, proportionately reduce the specimen size.	Not in full size but prescribed size.	As in BS 476.
How the specimen is heated	Wall: one side Floor: underside Beam: 4 sides Column: 4 sides	Wall: more than one side Beam: 3 or 4 sides	Wall: both sides	Beam: underside	No information.
Standard temperature/ time curve	$T = 345 \log_{10}(8t + 1) + 20$ T is in °C.	As in BS 476.	No mathematical expression provided. T is in °C.	No mathematical expression provided. T is in °C.	$\theta - \theta_o =$ $345 \log_{10}(8t + 1)$ θ is in K.
Test methods	Heating for loadbearing, insulation and integrity; Cotton pad for integrity.	As in BS 476.	Hose stream test and cotton pad test for integrity.	As in BS 476.	As in BS 476.
Performance criteria	Loadbearing: deflection or collapse Insulation: 140 °C (temp. rise) Integrity: cotton pad ignited	Insulation: 140 K (temp. rise)	Insulation: 139 °C (temp. rise)	Insulation: 260 °C (exact temp.)	Insulation: 140 K (temp. rise)

6. THE EQUAL AREA HYPOTHESIS

In 1920s, an "equal area hypothesis" was raised by Ingberg [25] to relate the fire load and fire severity. By carrying out a large number of experimental works, it was demonstrated that equal areas under two temperature/time curves (with a baseline of 300 °C) will have identical fire severity as shown in Fig. 4. The fire severity and the required FRP can be determined for a fire curve T_{real} of a real scenario by comparing with the standard temperature/time curve T_{stand}. The correlation can be expressed as:

$$\int_0^{FRP} T_{stand}\, dt = \int_0^{t_1} T_{real}\, dt \qquad (6)$$

Again, the heat flux received by the construction elements is not taken into account. The fire severity is considered as a function of temperature only.

7. REQUIREMENTS ON FIRE RESISTANCE PERIOD IN UK

- The Building Regulations 1991

The Building Regulations 1991 (the latest edition is The Building Regulations 2000, with minor amendments), one of the principal regulations in UK, is empowered by the Building Act 1984. The Approved Document B: Fire Safety [26] is a practical guide compliant with the requirements in Schedule 1 Part B of the Building Regulations 1991 in which technical requirements are expressed in functional form [27].

The minimum periods of fire resistance for elements of structure are also designated dependent on the purpose groups (analogous to functions or uses) of the building. In general, structural elements within a building deserve an FRP of 0.5 hour, such as floors, roofs, corridors, protected stairways and vertical shafts. A 1-hour FRP is specified for compartment walls separating different purpose groups. Four grades of FRP, including 0.5-hour, 1-hour, 1.5-hour and 2-hour, are generally taken advantage of in the requirements on each special purpose group as defined in the Document. The general grades of FRP along with those in other statutory instruments are listed in Table 6. The required FRP will be increased with the height of the top floor above ground in the building. In most of the purpose groups, structural elements of their basements are required to have an FRP of either 1 hour or 1.5 hours. A 2-hour FRP is required when the compartments are used as industrial occupancy or storage.

- Fire Precautions Act 1971 [28]

The following requirements are used in the Fire Precautions (Factories, Offices, Shops and Railway Premises) Order 1989, which only controls the fire safety at work. The minimum FRP is defined for different construction elements. Floor slabs should have an FRP of not less than 0.5 hour. Compartment enclosures in offices and shops should have at least 0.5 hour while factories need 1-hour FRP.

- Greater London Council (GLC) The London Building Acts (Amendment) Act 1939 [29] and London Building (Constructional) By-laws 1972 [30]

Building safety in Inner London was governed by its own system based on the London Building Acts 1930 to 1978 and the building by-laws until the Building (Inner London) Regulations came into effect in 1986.

The London Building Acts and By-laws are similar to the FRC code in the classification of FRP since they are specified for the intended functions of the building or occupancy and varied with the cubical extent. Compartments with a greater volume deserve a higher FRP. The general FRP grades include 0.5 hour, 1 hour and 2 hours. Elements of construction of basement storey require an FRP of not less than twice that required for the elements of construction of the building. But in no case the FRP can be greater than 2 hours.

8. LOCAL REQUIREMENTS ON FIRE RESISTANCE PERIOD

By reviewing the UK regulations and statutory instrument, the post-war Fire Grading reports in 1946 are said to be the most significant document throughout the century. The afterwards Model By-laws, London Building (Constructional) By-laws and the Building Regulations are all influenced by the reports.

Building Ordinance in Hong Kong was first issued in 1955. It was also influenced by the Fire Grading of Buildings since it had made reference to the London Building (Constructional) By-laws as London was the advocate of fire safety since the historical Great Fire of London.

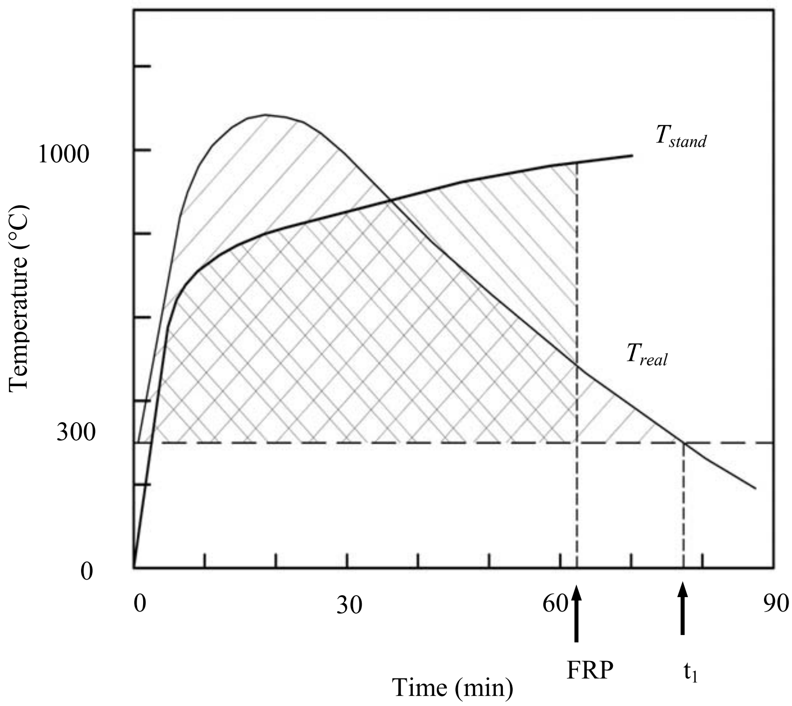

Fig. 4: The equal area hypothesis

Table 6: General grades of fire resistance period (in hours) of major elements of construction

Elements of construction	Local FRC code# [1]	Building (Construction) Regulations 1966* [30]	The Building Regulations 1991% [26]	Fire Precautions Act 1971 [28]	GLC London Building Act and By-laws# [29]
1. Wall	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	0.5, 1	0.5, 1, 2
Separating wall	2	4	1, 1.5, 2	-	4
2. Beam	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	-	0.5, 1, 2
3. Column	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	-	0.5, 1, 2
4. Floor	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	0.5, 1	0.5, 1, 2
5. Roof	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	-	0.5, 1, 2
6. Basement	4	1, 2	0.5, 1, 1.5, 2	-	1, 2

FRP depends on the intended functions of the building and cubical extent.
* Buildings having more than 3 stories should have at least 1-hour FRP.
% FRP depends on the intended functions of the building and height of top floor above ground or depth of the lowest basement.

New materials and building techniques have been evolved with the growing demand for residential and commercial premises by the increasing population in Hong Kong. Higher buildings are erected on the limited usable land, which lead to more stringent fire safety requirements [1] in order to protect the occupants and properties.

- FRC code [1]

The FRP requirements are specified for the intended uses of buildings. The grades used are 1 hour, 2 hours and 4 hours. Those for the major elements of construction, such as walls, beams, columns, floors, roofs and basements are prescribed to follow those for the various building uses, as shown in the following:

- 1-hour FRP is required for the main elements of construction, including walls, beams, columns, floors, roofs and basements in domestic buildings, hotel bedrooms, offices;
- 2-hour FRP is required in shops, restaurants, hospitals, assemblies, industrial buildings;
- 4-hour FRP is required for warehouses and basements.

Some of the FRP requirements can be slightly adjusted provided that their compartment volume does not exceed the specified value. For example, FRP can be reduced to 1 hour for shops, restaurants and hospitals if their cubical extent is less than 7000 m^3.

- Building Ordinance 1966

The first Building Ordinance in Hong Kong was issued in 1955. Some revisions were made until 1966, the Building (Construction) Regulations were presented and the requirement of fire resisting construction was shown in Part XIII. The technical requirements, as in the current code of practice, were listed in Table XVI. The definition of FRP pointed out that the requirement had made reference to BS 476: 1932 and LCC (the predecessor of GLC) London Building (Constructional) By-laws 1952.

The general grades of fire resistance in the 1966 edition are 0.5, 1 and 2 hours, which are dependent on the intended uses and also the volume or floor area of any one storey. The walls separating any adjoining buildings are required to have an FRP of not less than 4 hours while those separating compartments should have at least 2 hours. The construction elements of basements, on the other hand, should have twice the FRP required for those of the compartment in which the basement is located, but in no case, it should exceed 2 hours. Moreover, elements of construction in buildings with at least 4 stories should be provided an FRP of not less than 1 hour. The details of the FRP requirement are listed in Table 7, with the comparison with that of London Building (Constructional) By-laws 1972, the principal By-laws in Inner London. Both of them are similar in the grade of fire resistance, the classification of the building uses and the cubical extent of the compartment, however, they are divergent in the measuring units and the number of divisions in volume. The requirements on FRP of some building uses are classified by floor area of any one storey.

Table 7: Comparison of FRP requirement between Building (Construction) Regulation 1966 and London Building By-laws 1972

Uses	Building (Construction) Regulation 1966 [31]		London Building By-laws 1972 [30]	
	Volume / area*	FRP	FRP	Volume
Warehouse	708-1417 m^3	0.5	0.5	≤ 710 m^3
			0.5	710-1420 m^3
	1417-3542 m^3	1	0.5	1420-2130 m^3
			1	2130-3550 m^3
	3542-7083 m^3	2	2	3550-7080 m^3
Trade or manufacture	-	-	0.5	≤ 710 m^3
	-	-	0.5	710-1420 m^3
	1417-3542 m^3	0.5	0.5	1420-2130 m^3
			1	2130-3550 m^3
	3542-7083 m^3 • ≤ 697 m^2 • > 697 m^2	 1 2	2	3550-7080 m^3
Office or domestic	-	-	Nil	≤ 710 m^3
	-	-	Nil	710-1420 m^3
	1417-3542 m^3 or 93-332 m^2	0.5	0.5	1420-2130 m^3
			0.5	2130-3550 m^3
	> 3452 m^3 or > 232 m^2	1	1	≥ 3550 m^3
Partly for office & partly for trade or manufacture	-	-	0.5	≤ 710 m^3
	-	-	0.5	710-1420 m^3
	≤ 1813 m^3 or ≤ 232 m^2	0.5	1	1420-2130 m^3
	1813-3542 m^3 or 232-464 m^2	1	1	2130-3550 m^3
	3542-7083 m^3 or > 464 m^2	2	2	3550-7080 m^3
Partly for domestic & partly for trade or manufacture	≤ 907 m^3 or ≤ 93 m^2	0.5	0.5	≤ 710 m^3
	907-1813 m^3 or 93-232 m^2	1	0.5	710-1420 m^3
	> 1813 m^3 or > 232 m^2	2	1	1420-2130 m^3
	-	-	1	2130-3550 m^3
	-	-	2	3550-7080 m^3
Transformer	-	2	2	-
Garage	≤ 46 m^2	0.5	0.5	≤ 710 m^3
	46-93 m^2	1	1	710-1420 m^3
			1	1420-2130 m^3
	> 93 m^2	2	2	2130-3550 m^3
			2	3550-7080 m^3

* The original measuring unit is transformed to metric system.

9. ENGINEERING PERFORMANCE-BASED FIRE CODES

The standard fire tests have been the basis for complying with the law for several decades. Their ability to ensure building fire safety is illustrated by the absence of big fires caused by structural failure. But on the other hand, the necessary fire resistance period may be overestimated. It would lead to increased burden on capital cost. From the review of standard tests, it is also discovered that the real fire scenarios are not taken into account. Some full-scale fire tests carried out overseas have indicated that the structural fire protection is overrated by the standard tests.

Since the development of building materials and technologies is getting into a very fast track with the growing demand for buildings, these standard fire tests operated tens of years ago may not be able to adapt to the changes of the market.

As reviewed, temperature matching the standard temperature/time curve is the furnace temperature instead of surface temperature of the test specimen. But it is believed that temperature would be different between the two points. Heat transfer characteristics are varied by a number of factors, such as the types of fuel, thermal properties of the furnace walls, and the location of burners [18]. Two individual furnaces following the same standard temperature/time curve will also give different heat fluxes [32]. Therefore, the temperature received at the surface of test specimen is not necessarily equal to the internal temperature of furnace [33].

Moreover, total heat flux is the sum of convective and radiative heat flux. The latter will be significant in the case that the furnace wall of low thermal inertia is used. But flames, which give considerable amount of radiative heat flux, are excluded in the standard tests [34].

A new performance-based approach for those buildings unable to comply with the current prescriptive codes are now under development in Hong Kong. A tailor-made assessment method for the unique building is offered in this approach so that no exaggerated fire protection systems have to be installed. Fire safety design is examined by the appropriate assessment tool. The limitation of the standard fire tests can then be eliminated.

Performance-based fire codes are already adopted by a number of advanced countries. Performance criteria and design fire are the most important parts in the fire design under this new code [35,36]. For the fire resistance requirements, performance criteria for structural elements should be set to examine the fire design under the design fires.

A design fire should be determined [38] and there are some proposals [e.g. 39] in fitting the heat release rate Q (in kW) by a quadratic function in time t (in s) in terms of a fire growth constant α (in kWs^{-2}):

$$Q = \alpha t^2 \quad (7)$$

It will reach a steady value then and later on go through a decay phase [36,37]. All possible fire scenarios should also be investigated. They include building environment, configuration and thermal properties of the compartments, fire protection systems, air supply, probability of fire occurrence from past experiences and occupant factor. A "worst credible fire scenario" will be selected to act as the upper limit of fire risk analysis.

An evaluating tool, such as a computer modelling or mathematical analysis, is necessary to assess the performance of the fire safety design and determine whether it is satisfactory to the performance criteria. The one sufficient to protect the building can be used to replace the prescriptive requirements.

For setting up an EPBFC, design fire, fire scenarios, performance criteria, assessment tools are all areas requiring more effort [e.g. 35-37,40]. Detailed guidance on all those have to be provided in the fire code. For instance, the assessment method should be developed and achieve a sophisticated standard to ensure the accuracy and reliability of the judgement. Moreover, full-scale burning tests for those new materials in local industry should also be carried out and compiled as a database [41].

10. CONCLUSION

In the local FRC code, the FRP of structural elements are examined by the BS 476 according to the definition. However, it is found that the British Standards may be outdated or too conservative in coping with the new technologies. As reviewed, the BS 476: Parts 20 to 22 only examine one single element in each test. It implied that the structural stability gained from the connections with the adjacent elements of construction is out of consideration. However, it is believed to be able to increase the loadbearing capacity and integrity of the tested element to a large extent. The reduced specimen size resulted by the limited furnace capacity and also the ignorance of ventilation and thermal properties of compartments in the standard temperature/time curve would divert the fire performance far away from the real fire scenario.

Either overestimated or underestimated fire resistance design will be resulted from all these errors. Cost-effectiveness and fire safety can neither be ensured consequently.

In addition, there are only 10 classes of buildings in the local FRC code. Some of the building features which may have higher potential hazard are not required to have higher FRP. For instance, the popular atrium buildings are not included in the classification of building uses, but this design feature has been utilized in many large-scale complexes. The grand elegant space created in an atrium would impose extra fire hazard since smoke and flame would easily spread through different levels which are connected by the atrium.

Reform on the current fire codes system should therefore be carried out. The dominant prescriptive fire codes may still be applicable to some of the buildings after revision. In the meantime, EPBFC should be developed, following the global trend, to meet the demand of the complex buildings which cannot easily comply with the prescriptive codes.

Though EPBFC is not yet established in Hong Kong, the performance-based approach has been adopted as stated in the local code [1]. It is only for those new building designs having difficulties to comply with the prescriptive code. The traditional buildings should still follow the requirements in the prescriptive approach. A practice note [40] has illustrated the steps to perform this alternative approach in order to provide guidance for the Authorised Persons and the designers since it is a new idea to the local industry. Only outlines but not details are provided in this stage. For establishing the EPBFC, fire safety objectives should be firstly worked out so as to determine the steps followed, such as performance criteria. The sophistication of assessment tools, including computer models, laboratory tests or even hand calculations, should also be achieved, otherwise, the accuracy of assessment will be a query. Numerous nations have already adopted EPBFC in their legislation system. It is possible to make reference to their experience in working out the performance-based codes. However, not all the elements are suitable for the local environment. It is wise to integrate those appropriate with our effort, say a useful database on full-scale burning tests of the local materials [41], to complete this task. The professionals and fire engineers should also equip themselves with appropriate skills and knowledge to assist in the transition of fire codes.

Construction elements rated in fire resistance period can ensure fire confinement in the fire room and protect the neighbouring compartment from the effect of fire. Occupants can then have enough time for evacuation. It is mainly concerned about the post-flashover fire [43]. However, the pre-flashover fire should not be ignored. Flame spreading over wall-linings or carpets would definitely worsen the fire scenario at a much earlier stage.

For instance, in the popular entertainment karaoke establishments in Hong Kong, the walls separating the karaoke boxes from the main corridors are required to have an FRP of 1-hour in the local code [1], but no requirement is made on the partitions between the karaoke boxes. Aspects of flame spreading are not yet included in local codes on passive building design, though included in FSI code. The internal surfaces in the karaoke establishments are usually covered with linings and carpets. They are easy to ignite if there is no fire retardant treatment and a large influence on the heat release rate would then be resulted.

A study carried out before [43] on estimating the effect of the surface linings and carpets with different ignitability on the heat release rate showed that flashover is likely to occur in those small karaoke cubicles when non-fire-rated partition materials or retardant treatment are chosen. Studies showed that flame spreading would occur on painted surfaces [44]. Therefore, a great deal of attention should also be paid to flame spreading.

A long-term study is required for implementation of EPBFC for fire resisting construction. This is the first report on fire resisting construction in the local industry. The next step is to find out the fire safety objectives in the local code. It is an important element when carrying out the further steps, such as what performance is desired. In-depth research and investigation are necessary before coming up with the performance-based code to ensure our citizens' safety.

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