Application of Finite Element Modeling for Assessing the Fire Ratings of Beams

Vivek Jain and Govardhan Bhatt

Abstract In recent times, occurrences of fire accidents in buildings have become more frequent. To avoid such situations, the effects of fire need to be incorporated into structural design and detailing. In this study, the structural behavior of fire-exposed flexural elements is assessed at elevated temperatures and fire rating is determined in accordance with different methods of Eurocode-2. Structural moment capacity is also evaluated by incorporating the procedure of simplified calculation methods present in Eurocode EN 1992-1-2:2004. In this study, Wickstorm's method and transient thermal analysis using ANSYS are used for estimating temperatures in fire-exposed RCC members. Fire ratings obtained from the simplified calculation method and advanced calculation method of EN 1992-1-2:2004 is compared to fire ratings recommended in IS 456:2000 codal provisions.

Keywords Fire load · Moment capacity · Fire rating · ANSYS · Fire resistance · Fire load density

1 Introduction

Recent trends suggest that the number of fire accidents has increased all over the world due to which an upward trend in loss of lives can be observed. The major problem with fire is that it provides less time to handle the situation. The most important aim of a fire-structure analysis is to calculate the fire resistance time and performance of the structures under variation of temperature caused by fire. Fire resistance is the ability of the structure to resist fire spread, collapse, or other failures during exposure to a fire of specified severity or in other words it is the ability of a structure to fulfill its required functions for a specified load level, fire exposure, and time duration. In designing structures for fire safety, the critical step is to validate that the severity of the fire should not be greater than fire resistance of the structure. Different countries follow different national codes to handle structural fire-related issues. National

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Building Code of India (2016) and IS 456:2000 provides standard tables of structural elements of different dimensions having different fire rating. However, it does not provide a method for evaluation of reduced moment capacity of fire-affected structural elements. Eurocodes provide different methods for evaluation of fire resistance of concrete structural elements such as standard data and provisions, standard fire tests, advanced calculation methods, and simplified calculation methods. These prescriptive methods are derived from data obtained from standard fire resistance tests and do not consider the effect of many of the important parameters such as load level, fire scenario, and concrete strength [1]. In the present work, the fire ratings provided in IS 456:2000 [2] codal provisions are compared with fire ratings evaluated by 500 °C isotherm method provided in EN 1992-1-2:2004 [3]. Wickstrom's method is used for the evaluation of temperature in reinforcement bars. The temperature in reinforcement bars is also evaluated by thermal criteria using heat transfer analysis in finite element modeling.

2 Different Methods for Assessment of Fire Resistance

The various methods for evaluation of fire resistance of concrete structural elements are standards and provisions, standard fire tests, advanced calculation methods, and simplified calculation methods. These methods are briefly explained below.

2.1 Standards and Provisions

In most of the codes and standards, fire rating data are incorporated in the form of tabulated data. These data are quite useful in the initial stage of design. Fire resistance provisions in IS codes are provided in the form of tabulated data for different cross sections and reinforcement cover for various structural elements. One of the major drawbacks of this method is that detailed information about the background to the data is not provided in the IS codes.

2.2 Standard Fire Tests

Standard fire tests are performed on structural elements such as beams, columns, floors, or walls subjected to a standard fire exposure for determining fire resistance. This test is too expensive and time consuming and it provides less data for validation. Even though this method is more accurate and gives real behavior of structure, it cannot be performed on a regular basis due to higher expenses.

2.3 Advanced Calculation Methods

This method is a numerical method based on equations of heat transfer and theory of structural mechanics that is performed to evaluate thermal and mechanical response to assess the fire resistance. There are various finite element software available such as ANSYS, ABAQUS, SAFIR, etc., which use these numerical approaches for analyzing the fire response of structural members.

2.4 Simplified Calculation Methods

The methods discussed above are not suitable for daily routine design calculations. In such cases, simplified calculation methods are useful for predicting the capacity of structural elements EN 1992-1-2:2004 [3] provides two simplified calculation methods for estimating the capacity of fire-affected members: (a) 500 °C isothermal method (b) Zone method.

3 Introduction to IS Code Provisions

Fire resistance provisions provided in IS 456:2000 [2] and IS 1642:1988 [4] are the same and are present in the form of tabulated data. Minimum dimensions of reinforced concrete members and cover to reinforcement of various structural elements for fire resistance are shown in Tables 1 and 2.

Table 1 Minimum dimensions and nominal cover to meet the specified period of fire resistance for the RC beam (IS 1642:1989)

Nature of construction materials		Minimum dimensions (mm), excluding any finish for fire resistance of						
			0.5 h	1 h	1.5 h	2 h	3 h	4 h
1	Reinforced concrete	width	80	120	150	200	240	280
	(simply supported)	cover	20	30	40	60	70	80
2	Reinforced concrete	width	80	80	120	150	200	240
	(continuous)	cover	20	20	35	50	60	70

Table 2 Minimum dimensions and nominal cover to meet the specified period of fire resistance for RC slab (IS 1642:1989)

Nature of construction materials		Minimum dimensions (mm), excluding any finish for fire resistance of						
			0.5 h	1 h	1.5 h	2 h	3 h	4 h
1	Reinforced concrete	thickness	75	95	110	125	150	170
	(simply supported)	cover	15	20	25	35	45	55
2	Reinforced concrete	thickness	75	95	110	125	150	170
	(continuous)	cover	15	20	20	25	35	45

4 Stages in Fire Assessment of the Building

1. Estimate fire load/ fire load density,
2. Calculate equivalent exposure time,
3. Evaluate maximum temperature rise in the compartment,
4. Determine reduced cross section corresponding to 500 °C isotherm,
5. Calculate rebar temperature using penetration due to fire,
6. Calculate strength reduction factors of reinforcement,
7. Calculate forces in tensile and compressive reinforcement,
8. Determine reduced moment capacity,
9. Reduced moment capacity is compared with moment obtained due to fire load,
10. Determine fire resistance rating of structural members.

5 Calculation Procedure for Fire Resistance

Two methods suggested by EN 1992-1-2:2004 [3] for evaluation of the capacity of structural members at elevated temperatures are 500 °C isotherm method and zone method. 500 °C isotherm method has been used in the present paper to calculate the reduced moment capacity of structural elements. The procedure for calculating moment capacity of reinforced concrete members as per 500 °C isotherm method available in EN 1992-1-2:2004 [3] is given below:

1. The isotherm of 500 °C is evaluated for specified fire exposure, parametric fire, and standard fire.
2. Determine new cross section corresponding to 500 °C isotherm.
3. The temperature of individual reinforcing bars in tension and compression zones is evaluated from temperature profiles provided in Annex A of EN1992-1-2:2004. In this study, Wickstorm's method is used for the evaluation of the temperature of reinforcing bars.

4. The reduced strength of individual reinforced bars due to elevated temperature is determined.
5. The conventional calculation method based on limit state design as specified in IS 456:2000 is used for determining the ultimate load-carrying capacity for a reduced cross section with the strength of reinforcing members as obtained from the above step.
6. The design capacity is then compared with ultimate load-carrying capacity or alternatively estimated fire resistance with required resistance.
7. Fire ratings are then provided to the element which indicates the failure time of flexural members.

In this study, the beam is considered to be exposed to fire from both sides and bottom of the beam. In slab, it is considered to be exposed from the bottom only. So, in 500 °C isotherm method one-dimensional heat transfer is assumed in the slab.

6 Calculation of Temperatures

Empirical and graphical solutions are available as a design tool for calculation of temperature in any element.

6.1 Graphical Data

There are three sources available for temperature calculations based on graphical data:

1. The ISE and Concrete Society Design Guide (1978),
2. FIP/CEB Report (1978),
3. EN 1992-1-2.

6.2 Empirical Methods

These methods are based on data derived from furnace tests using curve fitting techniques or by superposition of simple solutions to the Fourier heat transfer equation. There are two such methods:

1. Hertz's method,
2. Wickstrom's method.

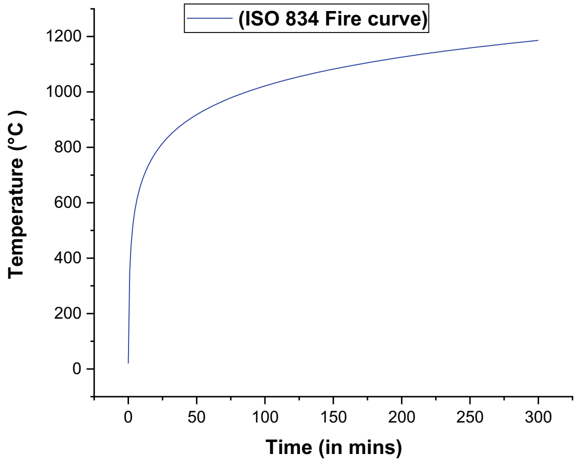


Fig. 1 ISO 834 fire loading curve representing temperature as a function of time

6.3 Wickstrom's Method

In the present study, Wickstorm's method is used for calculation of temperature. This method is based on the analysis of results from TASEF-2 [5]. It can be applied to exposure to either an actual compartment or the standard furnace test curve provided that the parametric curve in EN 1991-1-2:2004 [6] is used.

7 Fire Resistance Rating

It is defined as the length of time that the structure members will be able to resist collapse or can withstand when subjected to standard fire tests. It is expressed in hours (Fig. 1).

8 Finite Element Modeling

The thermal behavior of flexural elements is found out by using nonlinear finite element analysis. Using ANSYS, thermal analysis is performed on two -dimensional (2-D) models. For modeling of concrete, PLANE 55 (4-noded quadrilateral element) from ANSYS element library is used. In this study, the thermal properties of concrete specified in EN 1992-1-2:2004 [3] are used for the analysis in ANSYS. Thermal conductivity, specific heat, and density are temperature-dependent thermal properties that are used in the present work for thermal analysis. The variation of these thermal properties can be seen from Figs. 2, 3, and 4. Heat transfer from the fire to element is considered by convection on sides with a convection film coefficient of 25 W/m^2K

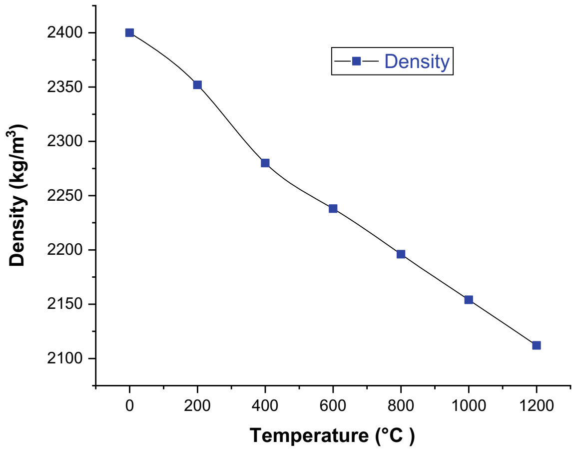


Fig. 2 Density of concrete as a function of temperature

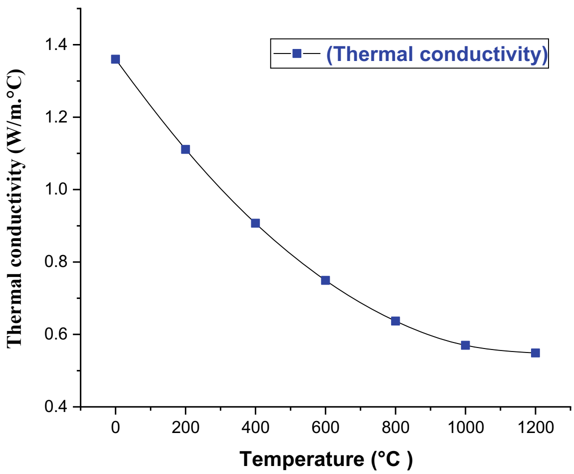


Fig. 3 Thermal conductivity of concrete as a function of temperature

[1]. For fire load ISO 834, fire loading curve is used in modeling of structural elements so that the temperature distribution of structure is established. The curve is defined according to the equation

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

where T is room temperature (°C), t is the time (in minutes), and T_o is the ambient temperature (°C).

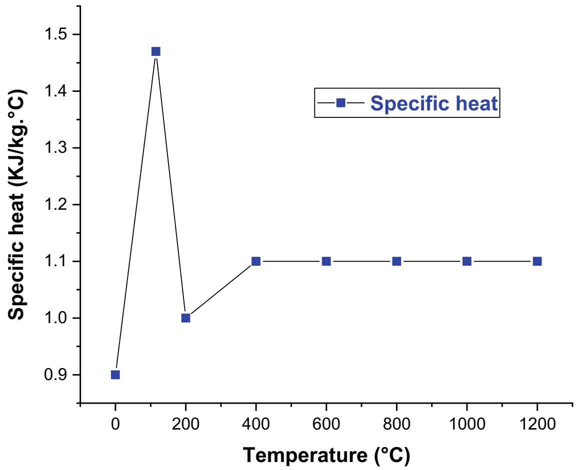


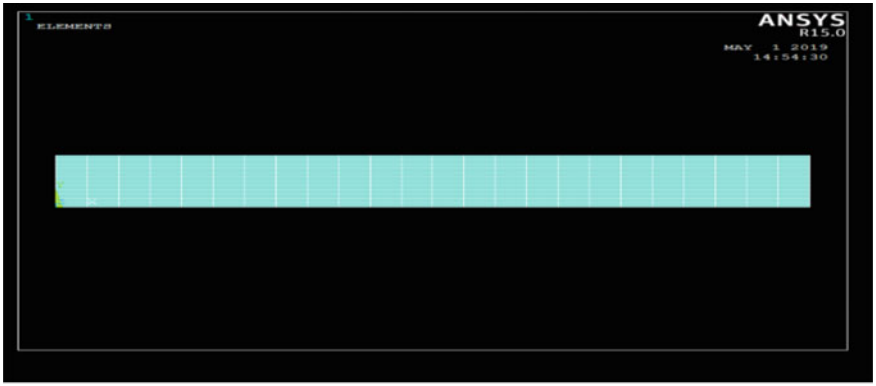
Fig. 4 Specific heat of concrete as a function of temperature

The same dimensions of structural elements as given for fire ratings in IS 456:2000 are modeled in ANSYS. Then appropriate meshing is done using mapped command. The details of cross section and meshing are shown in Figs. 5 and 6. Then the transient thermal analysis was carried out by dividing the fire load into number of time steps.

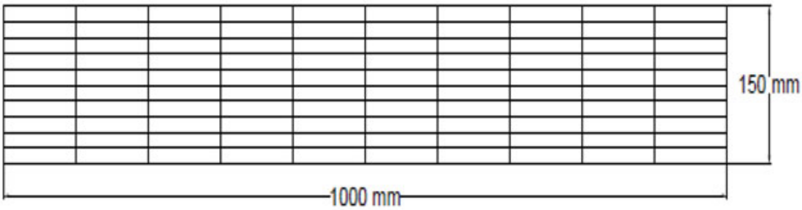
Figure 7. shows a temperature contour of the beam of cross Sect. 200 × 300 mm and for time of exposure 180 min. The variation of temperature in a slab of 150 mm thickness for the time of exposure 240 min is also shown in Fig. 8.

9 Comparison of Results of Various Assessment Methods

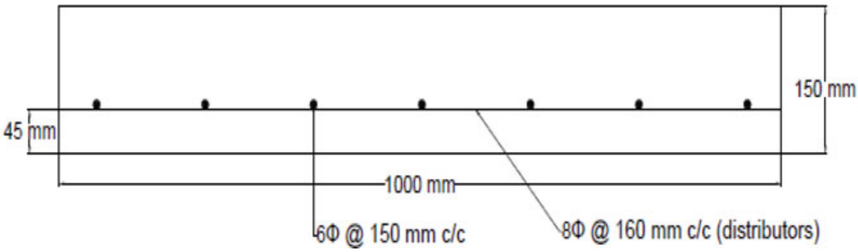
In this study, fire ratings of flexural members of different dimensions are evaluated using 500 °C isotherm method and ANSYS and then compared with tabular data provided in IS 456:2000 [2] codal provisions. 'The span length of all the beam and slab is taken as 2 m. The dead load and live load values are assumed based on IS codes and kept constant for all the beams and slabs. The fire ratings from 500 °C isotherm method are obtained by applying temperature reduction factors using Wickstorm's method. The fire ratings from ANSYS are obtained by considering thermal failure criteria. When the temperature in steel reinforcement exceeds the critical limiting temperature, i.e., 593 °C [1], failure of both beam and slab is considered. For 2-D thermal analysis, the reinforcement temperature is assumed the same as the concrete temperature at the corresponding position. The comparison of fire rating for beams and slabs are given in Tables 3 and 4.



(A)-Model of slab in ANSYS.



(B)-Discretization or meshing of slab .

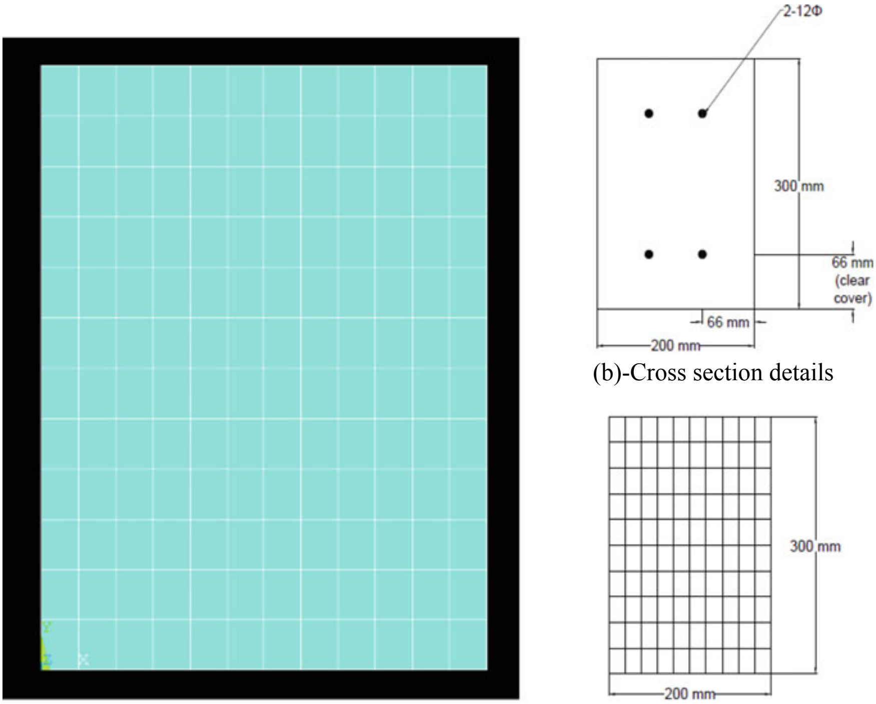


(C)-Cross-section details of slab.

Fig. 5 (**a**, **b**, and **c**) Discretization and cross section of RCC slab for finite element analysis in ANSYS

10 Conclusions

In this study, fire ratings of fire-exposed reinforced concrete beams and slabs based on Indian standard provisions, 500 °C isotherm method, and FEM is evaluated. From the numerical results and comparisons, the following conclusions are drawn as follows



(a)-Model of beam in ANSYS

(b)-Cross section details

(c)-Meshing of beam

Fig. 6 (**a**, **b**, and **c**) Discretization and cross section of RCC slab for finite element analysis

1. In beams with cover up to 30 mm, fire ratings given in IS code are nearly equal to the fire ratings value evaluated by 500 °C isotherm method and finite element method.
2. The beams of different dimensions and covers are observed to have a higher fire rating by 500 °C isotherm method than the IS code fire ratings.
3. The fire rating of slab specified in IS 456:2000 is lower than that observed by 500 °C isotherm method and finite element method.

Hence, the Indian standard provisions are observed to be more conservative than Eurocode-1992 and FEM in slabs and in beams of clear cover more than 40 mm. This study could be further utilized as a base for rigorous study in the respective subject.

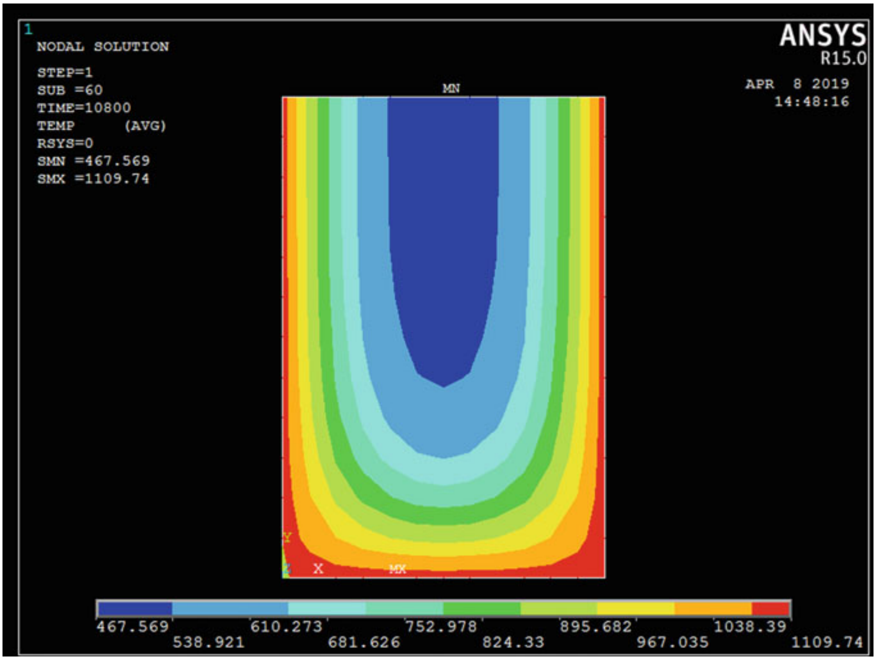


Fig. 7 Temperature contour for a beam of dimension 200 × 300 mm at t = 180 min

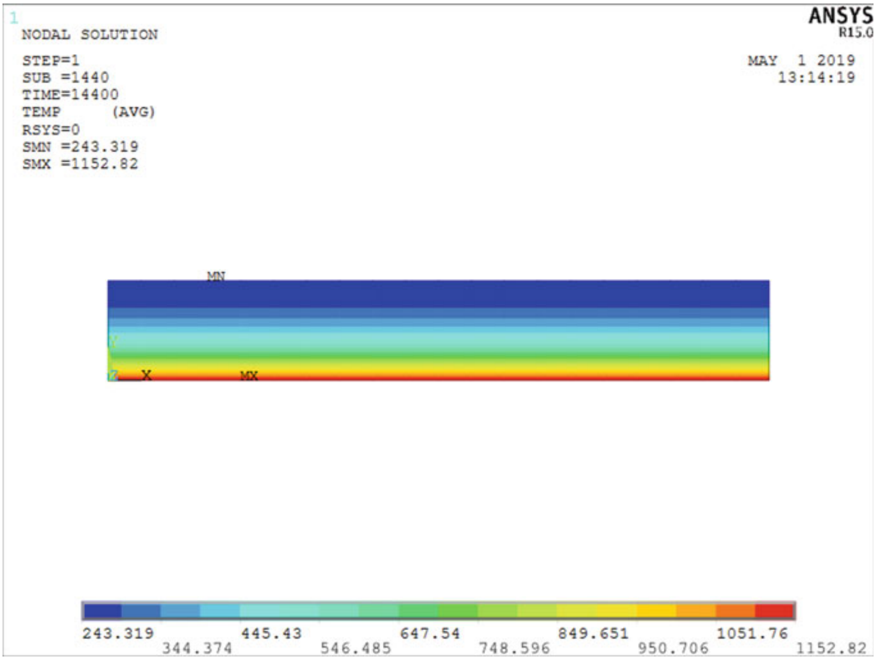


Fig. 8 Temperature distribution in slab of dimension 150 × 1000 mm at t = 240 min

Table 3 Comparison of fire rating of beam

Size (in mm)	Cover (in mm)	Fire rating (in minutes)			Moment capacity of IS code ratings	Moment applied at fire (DL + 0.5LL)
		IS 456:2000	Eurocode-1992 (500 °C isotherm method)	ANSYS		
80 × 150	20	30	44	31	7.23	1.84
120 × 150	30	60	62	64	2.11	1.91
150 × 300	40	90	112	82	5.48	2.25
200 × 300	60	120	177	180	9.91	2.44
240 × 300	70	180	192	199	3.75	2.59
280 × 300	80	240	242	232	1.27	2.74

Table 4 Comparison of fire rating of slab

Thickness (in mm)	Cover (in mm)	Fire rating (in minutes)			Moment capacity of IS code ratings	Moment applied at fire (DL + 0.5LL)
		IS 456:2000	Eurocode-1992 (500 °C isotherm method)	ANSYS		
75	15	30	81	65	6.09	2.44
95	20	60	116	123	7.90	2.69
110	25	90	151	145	9.11	2.88
125	35	120	221	189	9.72	3.06
150	45	180	312	> 240	8.82	3.38
170	55	240	406	> 240	8.90	3.63

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