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The Behaviour of Reinforced Concrete Slabs in Fire

By Zhaohui Huang *

ABSTRACT

In this paper a robust model is presented based on the previous layer procedure developed by the author to also take into account the effects of concrete spalling on the behaviour of concrete slabs under fire conditions. In this study, a detailed analysis of a uniformly loaded reinforced concrete slab subject to different degrees of concrete spalling under a standard fire regime is first carried out. Further, a series of analysis of floor slabs with different degrees of concrete spalling is also performed on a generic reinforced concrete building. A total of 16 cases have been analysed using different degrees of spalling on the slabs, with different extents and positions of localised fire compartments. It is clear that adjacent cool structures provide considerable thermal restraint to the floor slabs within the fire compartment. And it is evident that the compressive membrane force within the slabs is a major player in reducing the impact of concrete spalling on the structural behaviour of floor slabs in fire.

Key-words: concrete spalling; layer procedure; structural fire behaviour; concrete floor slabs.

* Corresponding author: Department of Civil & Structural Engineering, University of Sheffield, S1 3JD, UK Tel.: +44 (0) 114 2225710; Fax: +44 (0) 114 2225700; *E-mail: z.huang@sheffield.ac.uk*

1. Introduction

In the past two decades, a significant amount of research has been conducted into the performance of composite steel-framed structures in fire. For reinforced concrete structures, the research of the fire resistance of the structures was started in early 1970 and mainly focused on the behaviour of isolated members. In current design codes, such as Eurocode 2 [1] more advanced computer modelling methods are allowed. However, using current design practice, the influence of concrete spalling is ignored in the majority of the computer software developed, the concrete design against fire is still based on simplistic methods developed from standard fire tests which do not necessarily represent real building behaviour. This makes it very difficult, if not impossible, to accurately determine the actual level of safety achieved, or whether an appropriate level of safety could be attained more efficiently by using a performance-based design approach.

Concrete is a very common construction material. There is a widely-held perception among designers that reinforced concrete structures have good fire resistance compared with steel structures. This is based on the assumption that concrete cross-sections retain their integrity under fire conditions. However, in previous studies, considerable evidence has emerged which shows that spalling of concrete in accidental fires causes severe damage to concrete members [2, 3], especially for high-strength concrete and normal strength concrete with higher moisture content. In a full-scale fire test carried out on the Cardington concrete frame [3], the floor slabs were constructed using a grade C37 normal weight concrete. The average moisture content, measured seven days before the fire test, was 3.8% by weight. It is evident that the spalling of the floor slabs was extensive, and the bottom layer of steel reinforcement was exposed to fire attack, though collapse did not occur. This can possibly be attributed to a reasonably thick slab behaving in compressive membrane action. In recent years a number of numerical models have been developed for modelling the behaviour of reinforced concrete slabs in fire [4-7], but none of these have taken spalling into account.

Spalling is an umbrella term covering different damage phenomena which may occur to the surface layers of concrete members when exposed to fire. At present it is still not well understood, and therefore poses a risk to human life and property. Previous studies [8, 9] have shown that the mechanisms involved are very complicated. In most cases spalling seems to be due to a combination of pore pressure generated by boiling of the free water content, and thermal stresses due to extreme temperature gradients. It can be affected by a number of influences such as temperature gradient, internal thermal micro-cracking, cracking around reinforcement bars and strength loss due to chemical transitions. Given suitable combinations of load, thermal stress and pore pressure, any type of concrete can suffer spalling. In the HITECO research programme funded by the European Commission Khoury *et al* [10] developed a very comprehensive approach for predicting concrete spalling at elevated temperatures. Also Tenchev et al [11, 12] proposed a comprehensive coupled heat and mass transfer model to predict pore pressures within concrete under fire attack, and a new spalling criterion was developed taking account of both pore pressure and thermal tensile stresses [13].

However, published experimental data reveals many tests in which similar specimens exposed to similar conditions of load and heating demonstrated quite different results. It is very difficult, using the current theories, to explain these results. This may be because spalling is extremely sensitive to both the permeability and the tensile strength of concrete at elevated temperatures, and because both of these properties depend on the manner in which heated concrete cracks. This in turn is strongly affected by material parameters, including shape, surface roughness and aggregate distribution, and these are essentially random for each test specimen. In view of these uncertainties and the complexity of concrete spalling, current design codes [1] provide only simple guidance on the influence of spalling on the fire resistance of concrete structures. The models developed so far, for predicting concrete spalling and its influence on the thermal and structural behaviour of reinforced concrete structures in fire, still cannot be effectively used by structural engineers for performance based design of the fire resistance of concrete buildings. Hence, the main objective of the current paper is to develop a robust model which focuses particularly on the effect of spalling on the structural performance rather than attempting to develop a model for predicting the extent of spalling under specific conditions. Simple representations will be introduced to enable different degrees of spalling to be examined. The model will help designers to better understand the behaviour of reinforced concrete slabs in the presence of concrete spalling. The model also gives the designers a powerful tool to identify the upper and lower safety boundaries of the reinforced concrete slabs in fire. This approach was also adopted in previous research [14, 15] for modelling the impact of concrete spalling on the fire resistance of reinforced concrete beam-column frames.

At present there is no robust method available to assess the residual strength of reinforced concrete slabs after concrete spalling has occurred. Hence, a primary objective of this paper is to extend the current layer procedure developed by the author at the University of Sheffield [4, 5], to take into account the effects of concrete spalling on both thermal and structural behaviours of concrete slabs under fire conditions. Using a layering procedure and allowing some concrete layers to be "void" (with zero mechanical strength and stiffness; zero thermal resistance), the effects of concrete spalling on the thermal and structural behaviours of reinforced concrete slabs can be properly modelled. However, the model will not try to predict or to assess the likely levels of concrete spalling, but will examine the impact, if and when it happens to reinforced concrete slabs, on the global performance of concrete structures in fire.

First of all, a detailed analysis of a uniformly loaded reinforced concrete slab subjected to a standard ISO834 fire [17] was carried out. The slab was vertically supported on its four edges. In order to demonstrate the influence that spalling would have on the behaviour of the slab analysed, several different degrees of spalling were assumed in the analysis. In the study different support conditions on the four edges of the slab (ranging from simple support to completely fixed support in which rotation and lateral movement were fixed) were also applied. It is obvious that the support conditions for the slabs within the real building are in this range. Following that, a series of analysis of the above spalled-slab Cases with the same loading conditions was also performed on a generic reinforced concrete structure comprising ten floors. The building was designed to Eurocode 2 [1, 18] and represents a commercial office building with a 2 hour fire resistance rate. In order to study the interactions between the cool and hot zones of the structure, a total of 16 cases have been analysed using different degrees of spalling on the slabs, with different extents and positions of localised fire compartments.

2. Theoretical Background of the Program

In the 3D non-linear finite element procedure, which is the theoretical basis of the computer program, *Vulcan*, a reinforced concrete building is modelled as an assembly of finite beam-column and slab elements. It is assumed that the nodes of each of these different types of elements are defined in a common reference plane, as shown in Fig. 1. The reference plane is assumed to coincide with the mid-surface of the concrete slab element. Its location is fixed throughout the analysis.

In this program the beam-columns are represented by 3-noded line elements. Both material and geometric non-linearities are considered in the model. The cross-section of the beam-column is divided into a matrix of segments, and each segment may have different material, temperature and mechanical properties. The complications of structural behaviour in fire conditions, such as thermal expansion, degradation of stress-strain curves, failure of concrete segments by cracking and crushing, and yielding of reinforcement segments, are included. The detailed formulations of beam-column elements and the constitutive modelling of concrete and steel at elevated temperatures have been presented previously [15, 19].

For modelling reinforced concrete floor slabs a non-linear layered finite element procedure has been developed for predicting the structural response of reinforced concrete slabs subjected to fire [4, 5]. The procedure is based on the Mindlin/Reissner (thick plate) theory, and both geometric and material non-linearities are taken into account. The slab elements are sub-divided into concrete and reinforcing steel layers to take into account temperature distributions through the thickness of slabs, thermal strains, material degradation for each layer, and layer-by-layer failure based on stress levels at Gauss points. In this non-linear procedure the thermal and mechanical properties of concrete and reinforcing steel, such as thermal elongation, thermal conductivity, specific heat, compressive and tensile strengths of concrete and yield strength of reinforcing steel are changed at elevated temperatures. The material models specified in Eurocode 2 [1] for concrete and steel at elevated temperatures have been used and extensively validated in the previous researches [4, 5, 15, 20]. The research indicated that the material models proposed in the Eurocode 2 [1] are good representation of real material behaviour in fire. Hence, these models are adopted in this paper. For considering the effects of concrete spalling on the thermal and structural behaviours of the slabs under fire conditions a “void layer” is introduced to represent the spalled-concrete layer. It is assumed that the “void layer” has zero mechanical strength, stiffness and thermal resistance. Therefore, after the outer-layer concrete has spalled the inter-layer concrete will be exposed directly to the fire, so the fire boundary can be moved along the thickness of the slabs. These developments enable the program to quantitatively simulate the effects of concrete spalling on both the thermal and structural behaviours of reinforced concrete slabs under fire conditions.

The model described above was extensively validated against the test data in which the influence of concrete spalling was not considered [4, 5]. At present there are very limited available test data for concrete slab panels with significant spalling. In the full-scale fire test [3], all test data were lost after 23min test time due to the fire escaping the compartment through the top 325mm opening and burning out the cables which were connected to the data logger. Hence, it is difficult to use this test for validating the model. It is also well known that there are still no robust numerical models in existence which can accurately predict concrete spalling. Therefore, in this research some simplified and worst spalling cases were assumed to investigate the impact of concrete spalling on the global structural behaviour of floor slabs in fire. However, in the model the concrete spalling for each slab element is specified, hence, the non-uniform spalling can be modelled using a more fine-meshed model with different degrees of spalling.

3. Modelling of a Reinforced Concrete Slab

In this paper, the study was based on a generic 37.5m x 37.5m normal-weight reinforced concrete structure comprising ten floors with a 4.5m storey height and five 7.5m x 7.5m bays in each direction, which is subject to the ISO834 Standard Fire (see Fig. 2). The building is designed to Eurocode 2 [1, 18], and represents a commercial office building. As shown in Fig. 2 the floor slabs are supported on the beams along the column's grid lines. In the design calculations the floor slabs are designed as 25 simple supported slab panels of 7.5m x 7.5m. Also simple support condition is assumed for the 7.5m beams. Normal weight concrete with normal Portland cement and siliceous aggregates is used in this study. The characteristic strength of normal-strength concrete and reinforcing steel are assumed to be 45MPa and 460MPa, respectively. It is also assumed that a two hour fire resistance is required for the building. Therefore the nominal covers of the slabs, beams and columns for the required fire resistance is 25mm, 30mm and 25mm respectively [1].

According to the calculations the required thickness of floor slabs is 250mm with only two orthogonal tensile reinforcing steel layers (with the steel area of 646 mm^2/m for each layer). The dimensions of the cross-sections of beams and columns are 500mm x 350mm and 350mm x 350mm respectively. Fig. 3 shows the cross-section details of slabs, beams and columns. The reinforcing steel mesh of the slabs is continuous over the support beams and the reinforcing steel of the beams is also fully anchored into the columns. As mentioned in the previous section the slab floor is modelled as an assembly of layered slab elements. In this model the reinforcing steel bars are smeared into a steel layer with the same area of total cross-section of reinforcing steel bars. In this case, the thickness of each tensile reinforcing steel layer is 0.646mm which is equivalent to the steel area of 646 mm^2/m. Therefore, the smeared bottom tensile steel layer is at the position of 30 mm from the bottom surface of the slab. The characteristic loads are assumed to be:

Equivalent uniform load for self-weight of slabs and beams (assuming concrete density of 24kN/m^3): 7.5kN/m^2

Raised floor: 0.5kN/m^2

Ceiling and services: 0.5kN/m^2

Partitions: 1.0kN/m^2

Imposed load: 2.5kN/m^2

At the fire limit state, the total design load on the slab floors is 10.75 kN/m^2 when the partial safety factor of 1.0 and 0.5 are applied to the permanent and imposed loads, respectively. This loading is used throughout the example.

In order to investigate the influence of the support conditions on the behaviour of the slabs, detailed analyses of a uniformly loaded reinforced concrete slab, which has the same dimensions and loading condition as the floor slabs within one compartment of the generic building (see Fig. 2) subject to a standard fire regime was firstly carried out.

A big fire test was carried out on the full-scale seven-story in situ concrete building at BRE

Laboratories in Cardington on the 26 September 2001 [3]. The building was constructed between January and April 1998. In this test building each floor slab is normally 250mm thick and constructed using a grade C37 normal weight concrete. The average moisture content, measured seven days before the fire test, was 3.8% by weight and the total floor area of fire compartment is 225m^2. About 1000 ^{0}C of fire temperature was reached after 25min test time. It was observed in the test that spalling of concrete from the bottom of slab started at about 12min test time. The spalling of the floor slab was extensive, and the area and extent of spalling with reinforcement exposed to fire attack is approximate 160m^2 (70% of fire compartment floor area). Previous research [2, 3, 16] indicated that concrete spalling is likely to occur equivalent to before 30 min of the ISO834 Standard Fire test. Hence, in order to demonstrate the influence that spalling would have on the behaviour of the slab analysed, three concrete spalling cases referenced to time are assumed in this study, that is

Case 1: a 10mm thick surface layer exposed to fire is removed at 15 min;

Case 2: it is assumed that as in Case 1, the same amount of spalling occurs at the 15 min mark, and a further 10mm thick layer of concrete is subsequently also removed at 25 min;

Case 3: it is assumed that the same amount of the spalling happens as Case 2 at 15 and 25 min, and that a further 10mm thick layer of concrete is subsequently removed at 30 min after which the reinforcing steel is directly exposed to the fire.

In the analysis different support conditions on the four edges of the slab (ranging from simple support to completely fixed support) are also applied.

The first step of the analysis was to perform a thermal analysis on the slab. *Vulcan* has recently been extended by the author, to include a two-dimensional non-linear finite element procedure to predict the temperature distributions within the cross-sections of structural members subject to user-specified time-temperature fire curves. This was largely based on previous work [21] by the author. In this two-dimensional non-linear finite element procedure the thermal properties of the steel and concrete are assumed to change with temperature, and the influence of moisture initially held within the concrete and protection materials has been taken into account in the model. In this study the thermal properties given in Eurocode 2 [1] for concrete and steel have been adopted. As mentioned above the model is modified to take into account the effect of concrete spalling on the thermal behaviour of the reinforced concrete members. During the thermal analysis, when the assumed segment or layer is spalled the inner-part of the concrete is exposed directly to the fire, so the fire boundary can be moved within the cross-sections of concrete structural members. However, the concrete spalling cannot reach beyond the reinforcing steel cage of the members. The model was validated with some test data and reasonable agreement between model's predictions and tested results for the temperature of reinforcing steel in fire was achieved [15].

As mentioned above the model is modified to take into account the effect of concrete spalling on the thermal behaviour of the reinforced concrete members. The temperature histories of the reinforcing steel mesh in the slab for the three spalling cases together with the no-spalling case are shown in Fig. 4. It is evident that the thermal analysis model developed in this study can logically predict the significant effect of concrete spalling on the thermal behaviour of the slab. For the no-spalling case the temperature of the steel mesh at 120min is about 522 ^{0}C. If using this temperature as a reference temperature, the times to reach this temperature for the spalling cases are 78.5min, 48.5min and 32min for Case 1, Case 2 and Case 3 respectively. The temperatures of the cross-sections of the slab, generated by thermal analysis, were then used to carry out the structural analysis.

3.1. Structural Behaviour of the Slab with Simple Support on its Four Edges

Fig. 5 shows the vertical deflections at the centre of the simply supported slab for three spalling cases together with the no-spalling case. It is clear from the results that the impact of concrete spalling on the structural behaviour of the concrete slab is very significant for this support condition. Using the deflection criterion of span/20, 198 minutes fire resistance can be achieved for the no-spalling case, however, in Case 3, the spalled slab has only 33 minutes fire resistance. In order to examine the membrane forces within the concrete slabs, Figs. 6 and 7 show the vector plots distribution of the principal membrane tractions (forces per unit width) at the Gauss points of the slab elements at 198 min and 33 min for the no-spalling case and Case 3 (spalled), respectively. In these plots, the lengths of the vectors are proportional to their magnitudes; thin vector lines denote tension and thick lines denote compression. It is interesting to find that the distributions of the principal membrane tractions in the slabs for two cases are very similar, in which the central deflections of two cases are the same. The analysis results indicated that tension cracks were formed at almost all Gauss integration points of the top layer within the central area of the slab. The results show strong evidence indicating that for simple supported edges, the main load-carrying mechanism of the slabs subjected to large deflection in fire is due to the tensile membrane actions. It is also evident that the tensile membrane tractions in the centre of the slab are mainly resisted by the steel meshes. In Case 3, it is assumed that 30mm thick of concrete layers was spalled from 15min to 30min, and exposed the steel mesh directly to the fire at 30min, which is why the temperatures of the steel mesh were increased dramatically after 30min (see Fig. 4). That is the main reason why the central deflections of the Case 3 slab (spalled) run away after 33 min (see Fig 5).

3.2. Structural Behaviour of the Slab with Fixed Support on its Four Edges

The support condition of a slab panel within a real building is different with simple or completely fixed support conditions and depends on the location of the slab panel in the building. However, the real support condition of a slab panel is within these two idealised cases. Therefore, in order to give the lower and up bound for the behaviour of a slab panel under fire conditions, the same slab panel was modelled using completely fixed support conditions on its four edges. This means the rotational and translational movements on the four edges of the slab were fixed during the analysis. Comparison of the vertical deflections at the centre of the slab for three spalling cases, together with the no-spalling case is shown in Fig. 8. It can be seen from the results that the impact of concrete spalling on the structural behaviour of the slab subjected to such support conditions is very insignificant. At least three hours fire resistance can be achieved for the Case 3 spalled-slab, however, there was only 33min fire resistance for the slab subject to simple supported condition. The principal membrane tractions within the slab at 180min for the no-spalling case and Case 3 (spalled) are shown in Figs. 9 and 10, respectively. It is evident that in both cases the principal membrane tractions in the slabs are in compression. Again, the distributions of compressive membrane tractions are almost identical for both cases. Therefore, the compressive membrane action is the main load-carrying mechanism of the slab for this support condition. The results shown in the Figs. 9 and 10 explain why the effect of concrete spalling on the structural behaviour of the slab is insignificant. Due to the slab being mainly subjected to compressive membrane action, the steel mesh plays a very little role in such a load-carrying mechanism, hence the influence of reinforcing steel mesh is negligible.

In order to identify the influences of thermal restraint on the structural behaviour of the slab, the same slab was modelled without thermal restraint but with a rotational degree of freedom fixed to represent the slab's continuity over the supports. Fig. 11 shows the comparison of the vertical deflections at the centre of the slab for three spalling cases together with the no-spalling case. It is obvious that the influences of concrete spalling on the behaviour of the slab are very significant. The results confirm that thermal restraint is a key factor to generating compressive membrane action for improving the performance of spalled concrete slabs in fire conditions. This is further confirmed by the results shown in Fig. 12.

4. Analysis of Reinforced Concrete Frame Structure in Fire

In order to investigate the behaviour of reinforced concrete floor slabs in a real building, the research in this paper was based on a generic normal weight reinforced concrete structure (as mentioned in the above section) comprising ten floors with five bays in each direction, which is subject to the ISO834 Standard Fire (see Fig. 2). It is also assumed that a two hour fire resistance is required for the building.

4.1. Structural Behaviour with Whole Floor Heated

In a real building fire, the fire initially start at one location then spread from one compartment to the others. Therefore, the behaviour of whole building is depended on the fire development with time. It is very difficulty to model it precisely. In this study, for simplicity, it is firstly assumed that the whole seventh floor of the building is engulfed in fire which represents the one of the worst scenarios. Because of the inherent symmetry of the case, only a quarter of the structure was modelled. The first step was to perform a thermal analysis using *Vulcan*. In the analysis the slabs were heated from bottom surface and beams were fired from three sides in which the top surface of the beam was fully connected to the slabs. Also the columns were assumed to be totally engulfed in fire. In order to concentrate on the behaviour of slabs within the building in fire it is assumed that no concrete spalling happens on beams and columns, in other words, it is assumed that all the reinforced concrete cross-sections of the beams and columns remain intact. The temperature histories of the main reinforcing steel bars in the beam and column sections are shown in Fig. 13. The maximum temperatures of reinforcement at 120min and 180min are about 530°C and 660°C respectively. It is obvious that the concrete covers provide very good thermal insulation to the reinforcement during the fire. Three concrete spalling cases for the slabs used in previous section are used here again. Hence, the temperatures of the steel mesh in the concrete slabs are the same as shown in Fig. 4. The temperatures of the cross-sections of the members, generated by thermal analysis are then used to carry out the structural analysis.

The predicted deflections at the key positions, A, B, and C within the structure analysed (see Fig. 2) are presented in Figs. 14, 15 and 16, respectively. It can be seen that the analysis was stopped at 165min for the no-spalling case. This is due to the buckling of Column B2, however the fire resistance of this case is well beyond the design resistance of 120min. It is evident that the effects of concrete spalling on the deflections of the floor slabs at three key positions are very significant. Due to the fact that the whole floor is heated, the thermal restraint to the slabs and beams is only provided through the columns. Therefore, the behaviour of floor slabs in fire is different compared to the behaviour at ambient temperature. For the non-spalling case the deflection at position C is bigger than the deflection at position B. This is due to the second order effect generated by the thermal restraint provided by columns. From previous section (see Figs. 11 and 12) it is clear that the thermal restraint is the main factor to reduce the effect of spalling on the behaviour of slabs. The continuity of the slabs has very limited influence on the behaviour of spalled slabs. For the 'whole floor heated' case the magnitude of thermal restraint provided by columns is relatively small. Hence, the impacts of spalling on the deflections at positions A, B, and C are very similar and are not very different compared to the simple support case shown in Fig. 5. Figs. 17 and 18 show the distributions of the principal membrane tractions in the slabs at 165min for the non-spalling case and at 49min for the Case 3 spalling respectively. The results confirm that in this case the tensile membrane action is the main load-carrying mechanism of the floor slabs at large deflections in which steel mesh is the key component in the slabs to resist tensile membrane forces in the central area of the fire compartment. The concrete covers to the steel mesh were reduced by the concrete spalling, hence the temperature of the steel mesh increased dramatically, especially after the steel mesh was directly exposed to the fire (see Fig. 4). In consequence, the strength of steel mesh was reduced significant at elevated temperatures.

This is the main reason why only less than 49min fire resistance can be achieved for the Case 3 spalling, where as in the no-spalling case the fire resistance was 165min.

4.2. Structural Behaviour with Fire Compartments in Different Locations

In order to study the interactions between the cool and hot zones of the structure, a series of analyses has been carried out for different extents and positions of localised fire compartments. Three different locations were modelled, as indicated in Fig. 19. The temperature distributions for the structural members within the fire compartment are assumed to remain the same as above. The structure beyond the fire compartment is assumed to remain at 20°C.

Fig. 20 shows the deflections, at the centre of the fire compartment of FC-I (see Fig. 19), with time for the no-spalling and spalling cases. The distributions of the principal membrane tractions within the floor slabs at 180min for the no-spalling case and at 59min for the Case 3 spalling are shown in Figs. 21 and 22, respectively. It can be seen that the behaviour of the floor slabs within the fire compartment is very similar to the case with whole floor engulfed in fire. In this corner compartment little in-plane restraint is capable of being provided by the surrounding cool structure, and so the floor slabs within the corner bay need to be almost self-equilibrating in the horizontal plane. This means that at large deflections the tensile membrane tractions within the central zone of the floor slabs are balanced by the compression forces formed around the perimeter of the fire compartment. These are made possible by the presence of vertical support due to the concrete beams, which forces the slab to deform in double curvature, and thus to generate the membrane traction fields shown in Figs. 21 and 22. The load-carrying capacity of the slabs is increased significantly due to this tensile membrane action, in which the steel mesh is a key component. This is why concrete spalling has such big impact on the floor slabs within this fire compartment.

The deflections of the floor slabs at the centre of the fire compartment of FC-II (see Fig. 19) are presented in Fig. 23 for the no-spalling and spalling cases. It is interesting to see that the influence of the concrete spalling on the floor slabs is significantly reduced, even for the Case 3 spalling in which the steel mesh is directly exposed to fire after 30min. This is due to the fact that the floor slabs in the fire compartment are subjected to the large restraint provided by the surrounding cooler structures. Hence, the floor slabs behave as compressive membrane action during the fire. Figs 24 and 25 show the distributions of the principal membrane tractions in the slab at 160min for the no-spalling and spalling cases, respectively. It is evident that the floor slabs within the fire compartment are subjected to compressive membrane forces for both cases and concrete spalling has very little influence on them. The load-carrying mechanism of floor slabs is mainly through compressive membrane actions. Hence, the influence of the steel mesh is very limited in this case.

The fire compartment of FC-III (see Fig. 19) is located at centre of the building. Therefore, the thermal restraint provided by the surrounding cool structures is significant larger compared to the FC-II case. Fig. 26 shows the deflections of the floor slabs at the centre of the fire compartment for the no-spalling and spalling cases. Again, the results confirm that the effect of concrete spalling on the deflection of the floor slabs is very small. The distributions of the principal membrane tractions in the slab at 170min for the no-spalling and spalling cases are shown in Figs. 27 and 28, respectively. In this case the fire compartment is located in the centre of the building. Therefore huge compressive membrane forces within the floor slabs in the fire compartment are generated due to high restraint provided by the surrounding cool structures. Same as the FC-II case, impact of concrete spalling on the behaviour of floor slabs is greatly reduced by large compressive membrane actions. Hence, the influence of the steel mesh on the load-carrying capacity of the floor slabs is negligible.

5. Conclusions

In this paper a robust model is presented based on the previous layer procedure developed by the author, to take into account the effects of concrete spalling on both thermal and structural behaviours of concrete slabs under fire conditions. Using a layering procedure and allowing some concrete layers to be “void” (with zero mechanical strength and stiffness; zero thermal resistance) the effects of concrete spalling on the thermal and structural behaviours of reinforced concrete slabs can be quantitatively modelled. In this study, firstly a total of 12 detailed analyses were carried out for a uniformly loaded reinforced concrete slab, subject to different degrees of concrete spalling and support conditions under a standard fire regime. Further, a series of analysis of the floor slabs with different degrees of concrete spalling was also performed on a generic reinforced concrete structure comprising ten floors and five bays in each direction. In order to study the interactions between the cooler and hotter zones of the structure, a total of 16 cases have been analysed using different degrees of spalling on the slabs, with different extents and positions of localised fire compartments.

This research for the first time numerically indicated that the effects of concrete spalling on the thermal behaviour of concrete slabs are very significant. However, the impacts of the concrete spalling on the structural behaviour of reinforced concrete slabs are largely dependent on the degree of thermal restraint provided to the slabs. It can be concluded from this research that the compressive membrane force is a major player in reducing the impact of concrete spalling on the structural behaviour of concrete floor slabs within the fire compartment. Therefore, concrete spalling has very little influence on the fire resistance of concrete floor slabs in the central fire compartment of the building due to the high thermal restraint provided by surrounding cool structures. However, concrete spalling can significantly reduce the fire resistance of the floor slabs in the corner bay of the buildings because there is very little thermal restraint in those compartments.

The results presented in this paper systematically answers the questions of why more severely-spalled floor slabs within central areas of the buildings did not collapse either in the previous experiment or in accidental fires.

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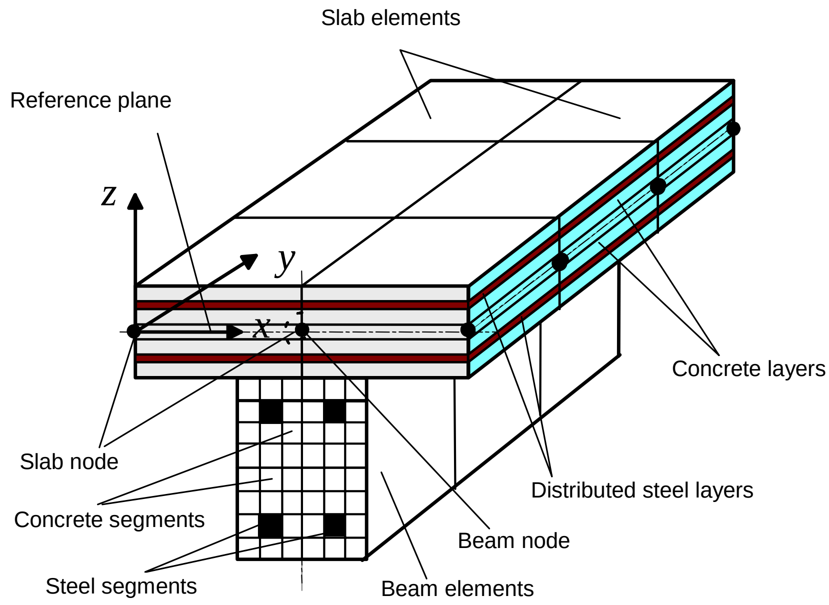
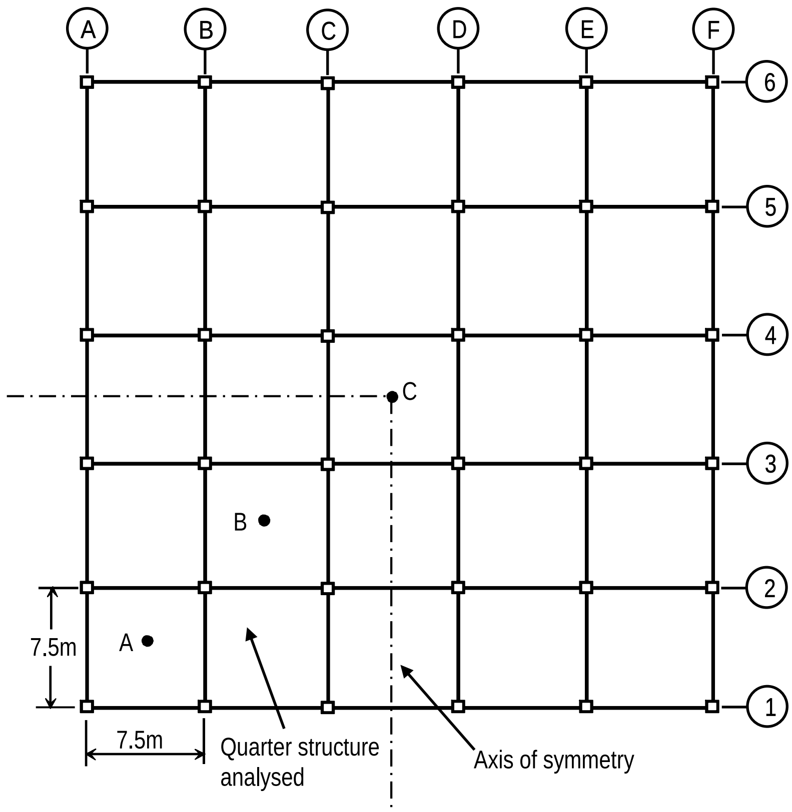


Fig. 1. Division of reinforced concrete structure into beam and slab elements.



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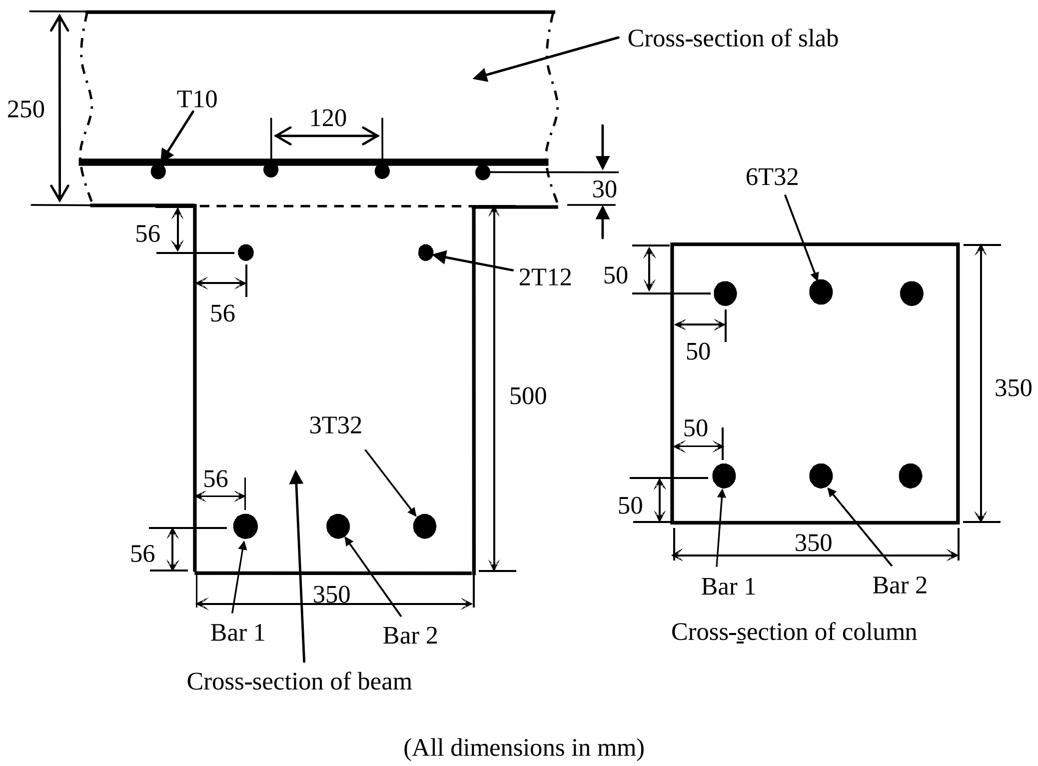

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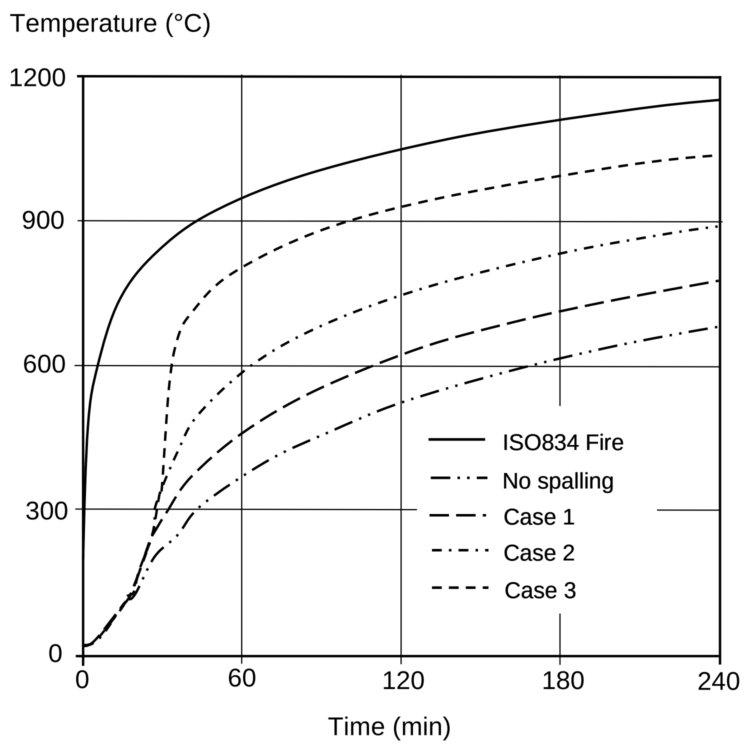

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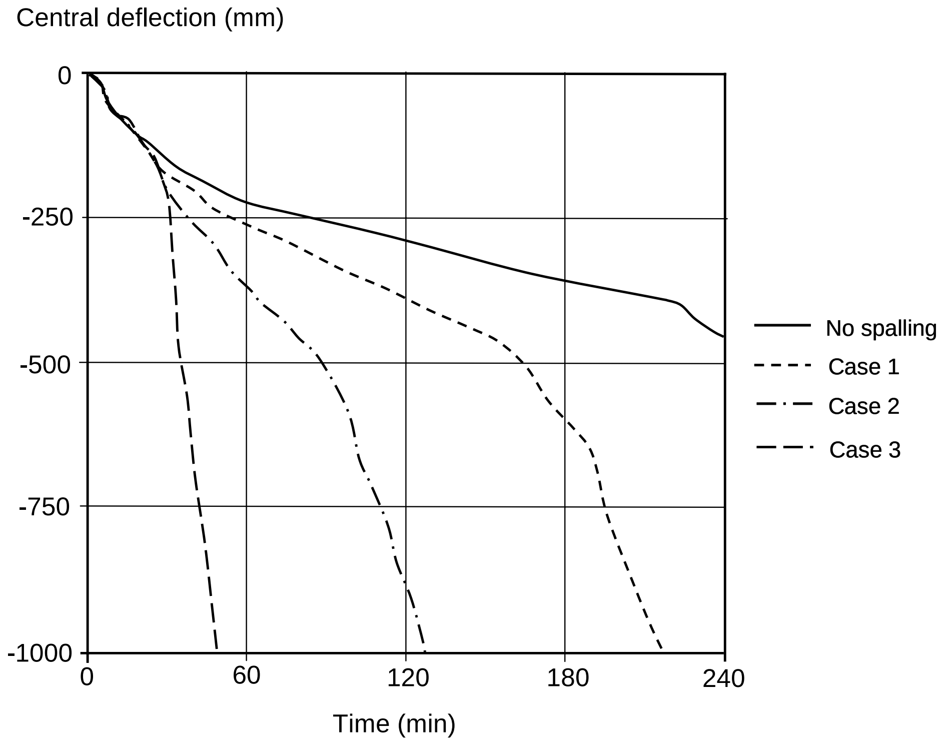

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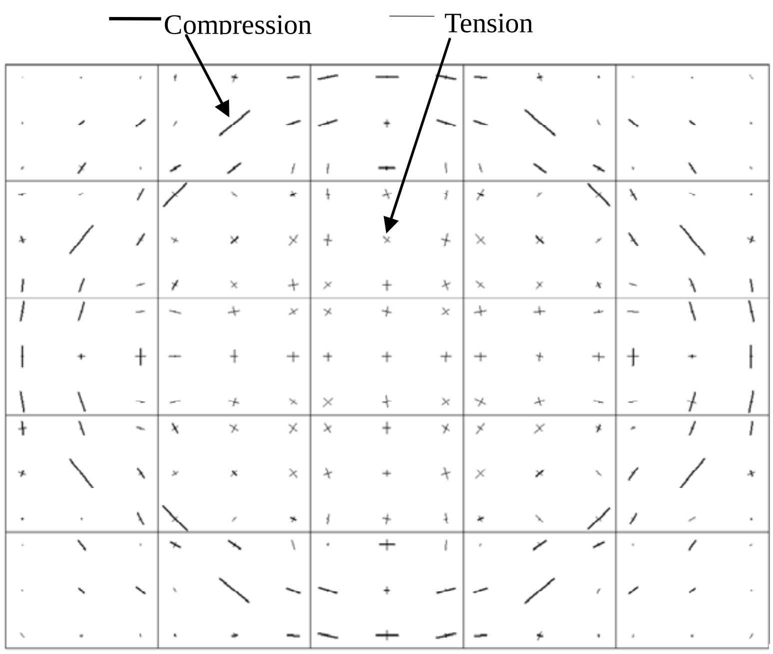

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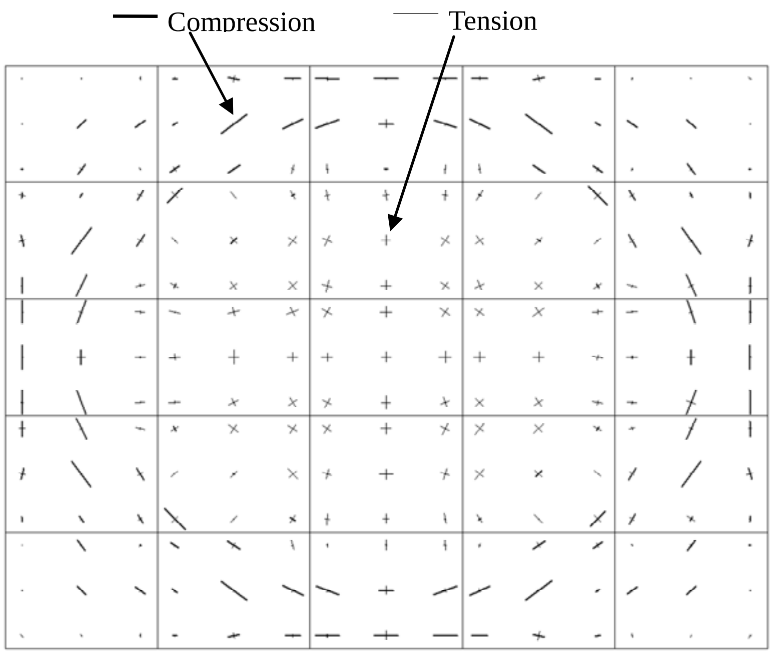

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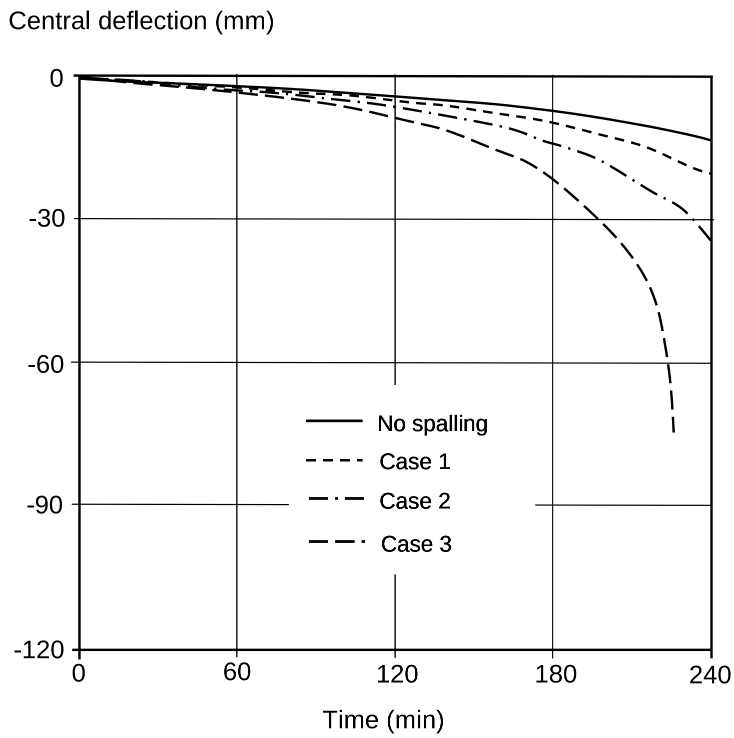

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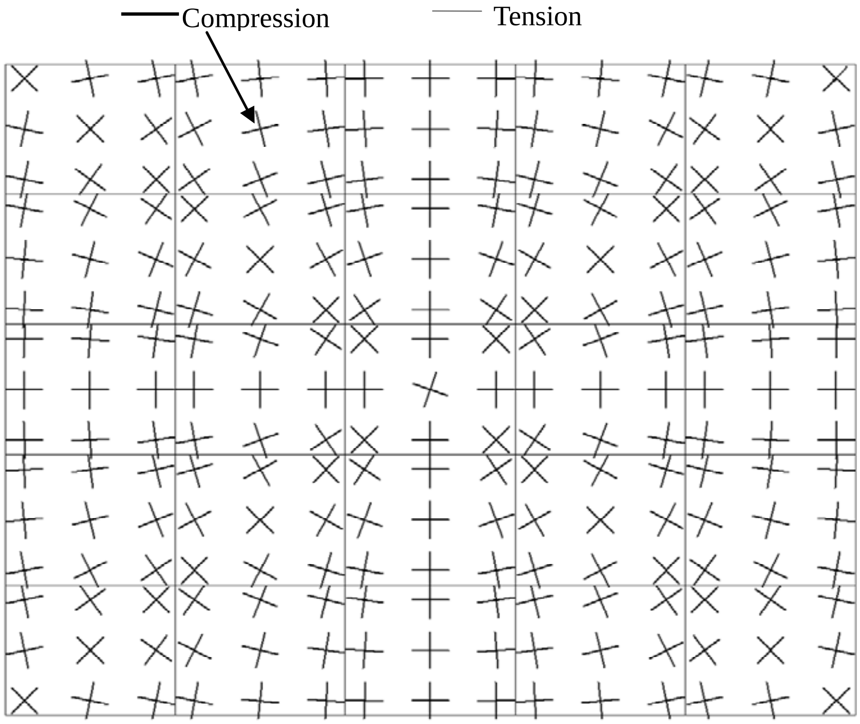

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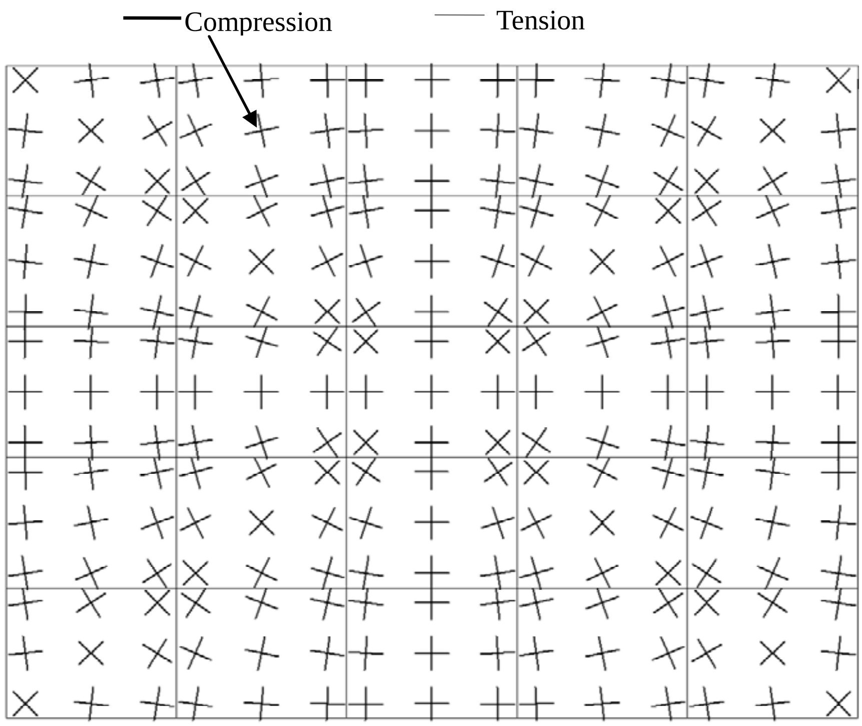

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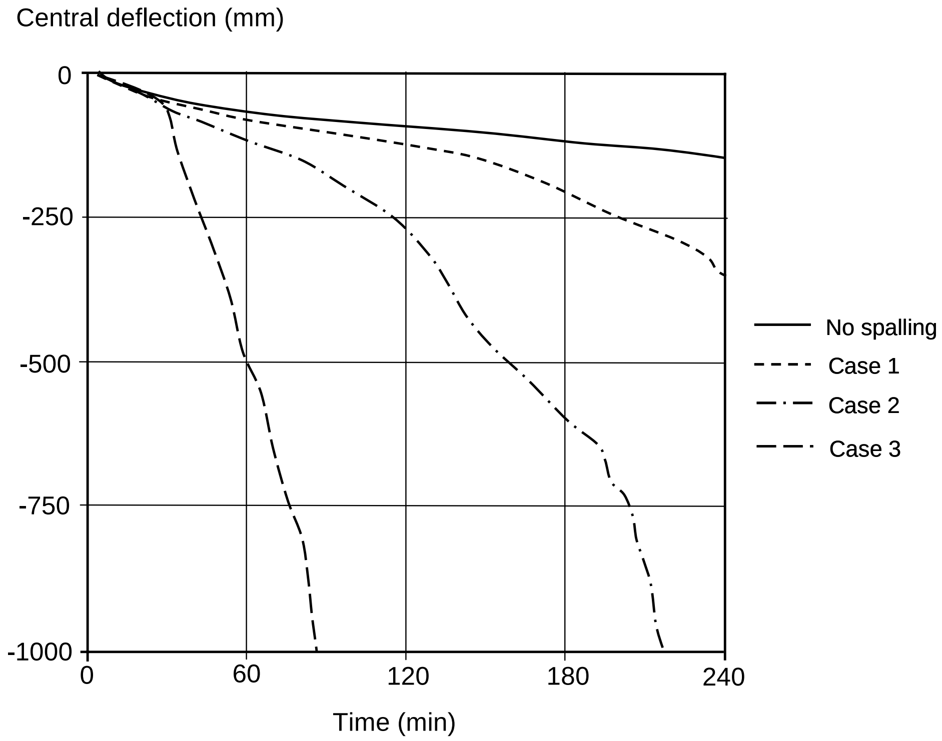

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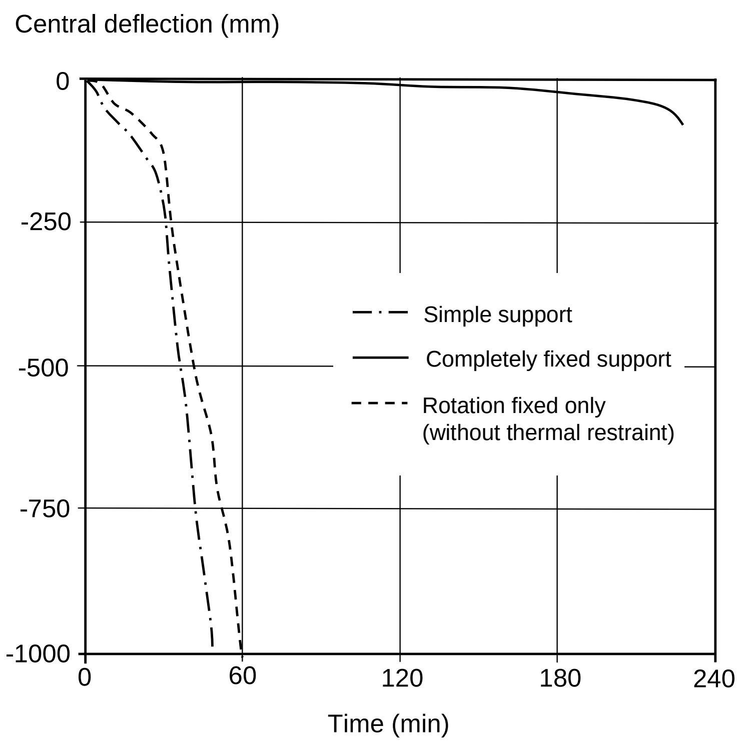

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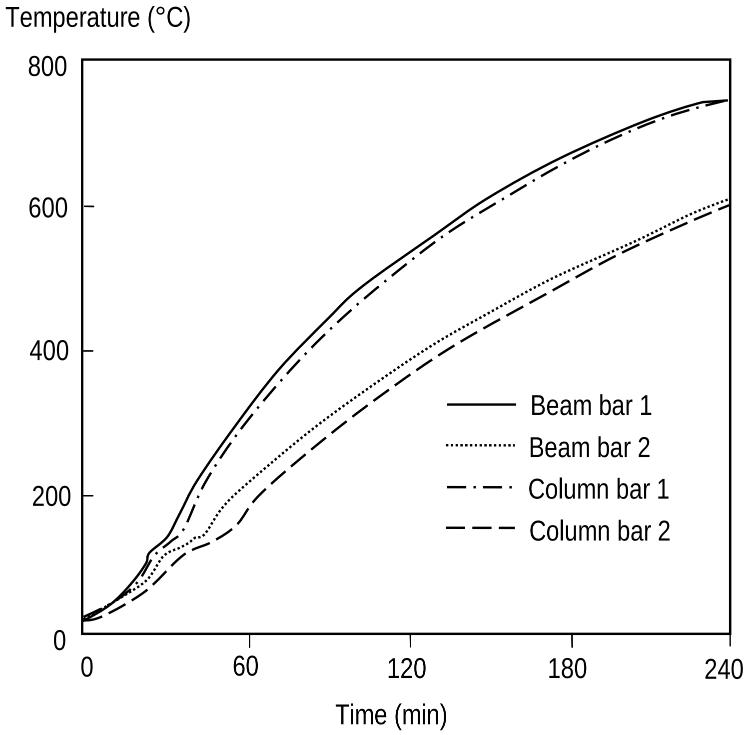

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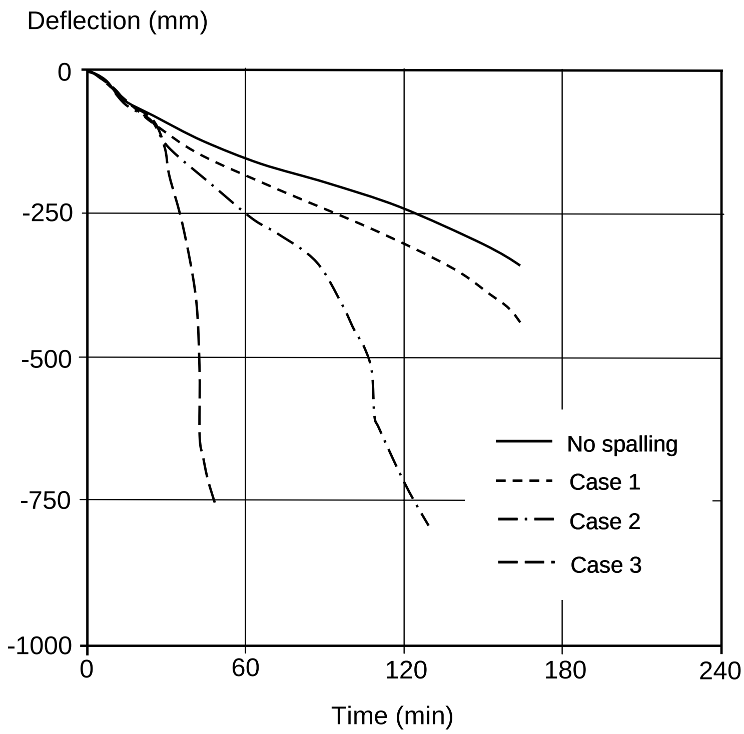

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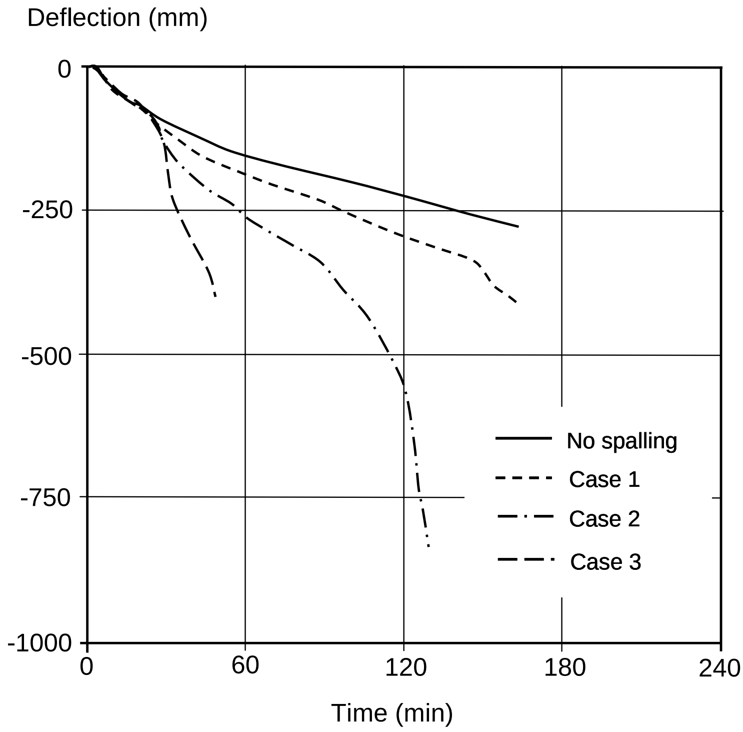

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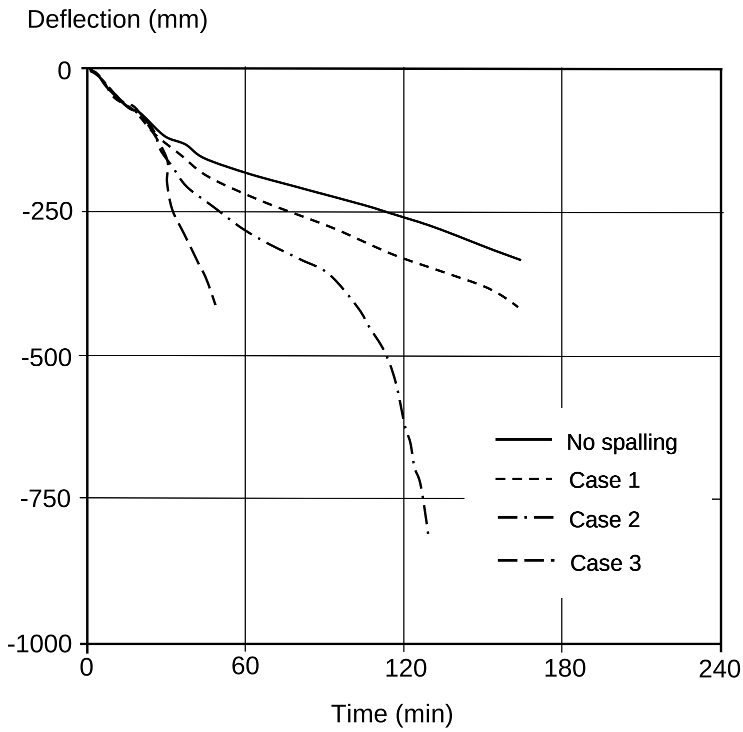

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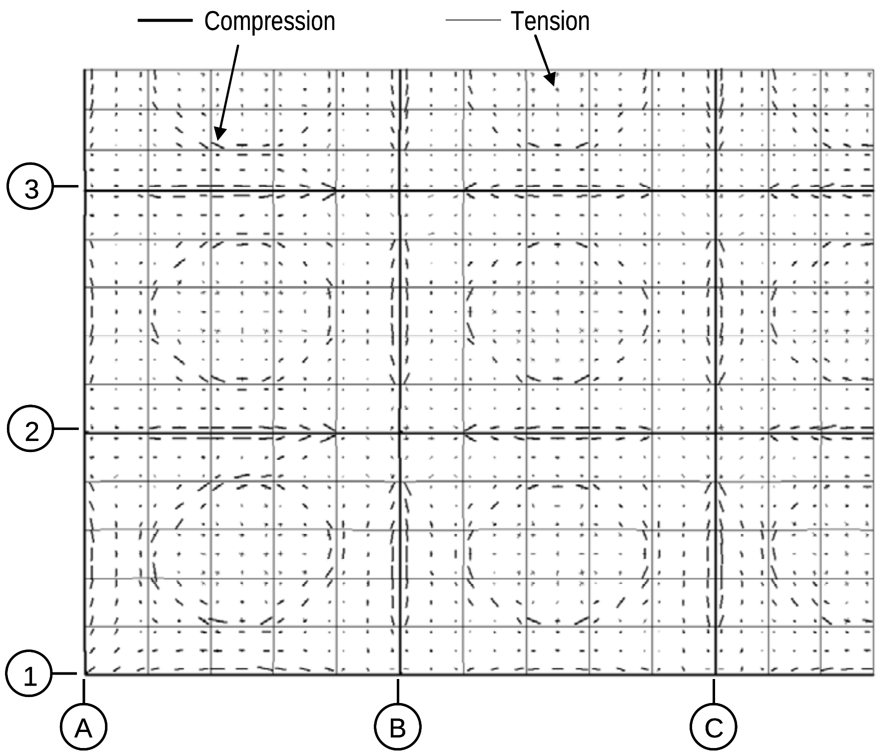

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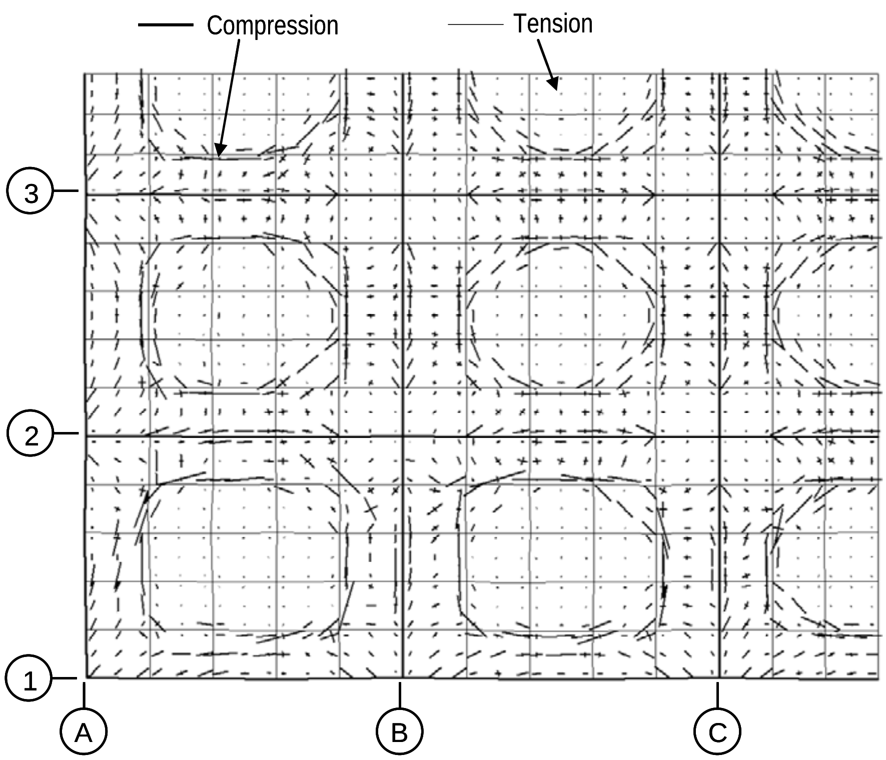

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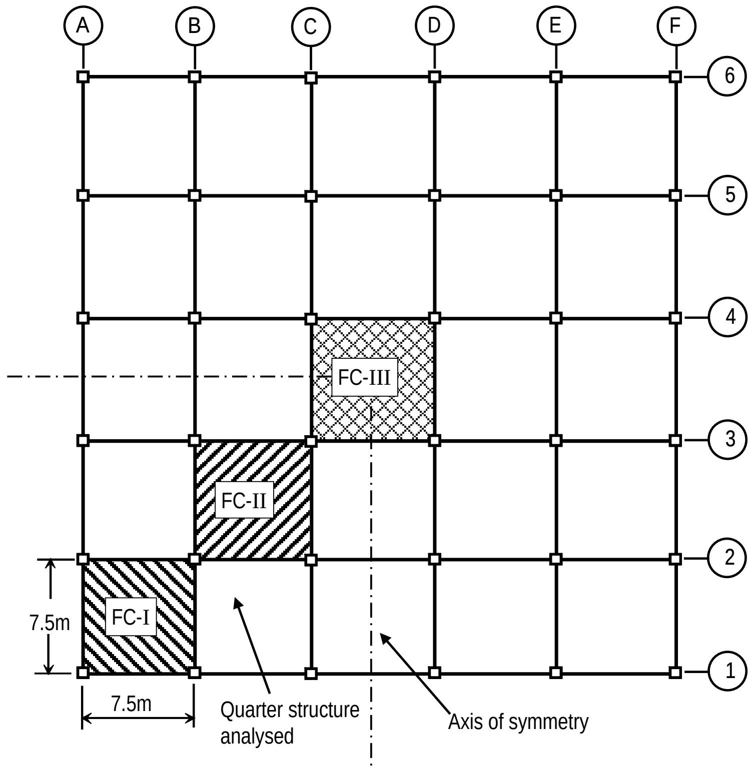

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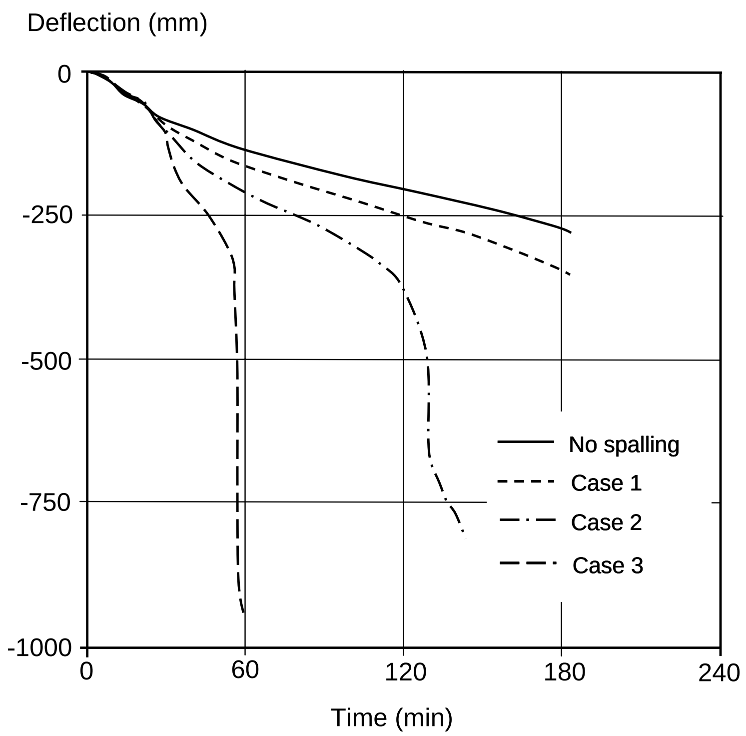

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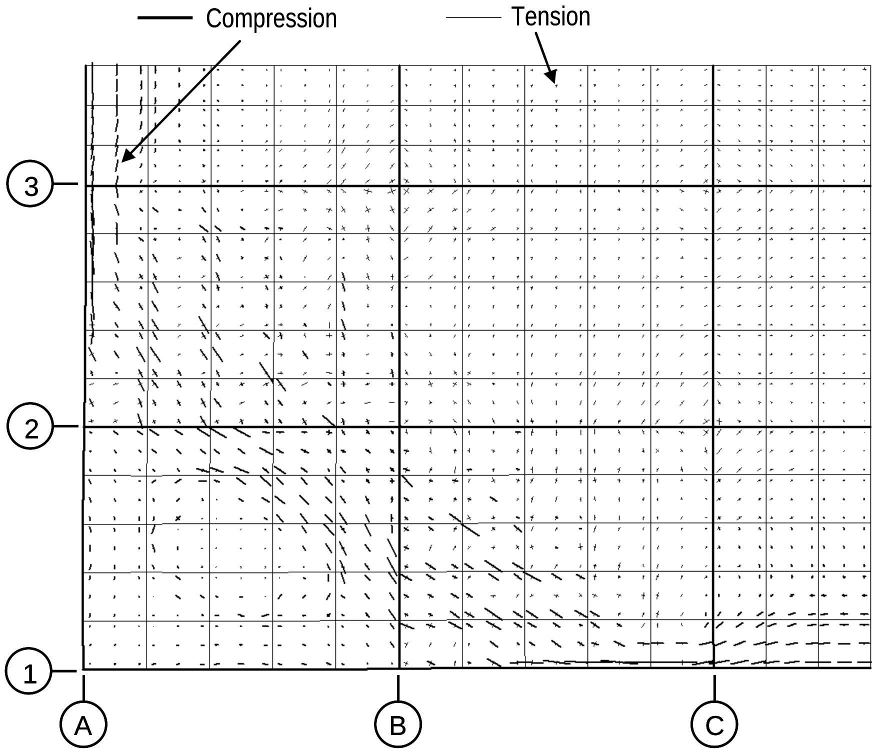

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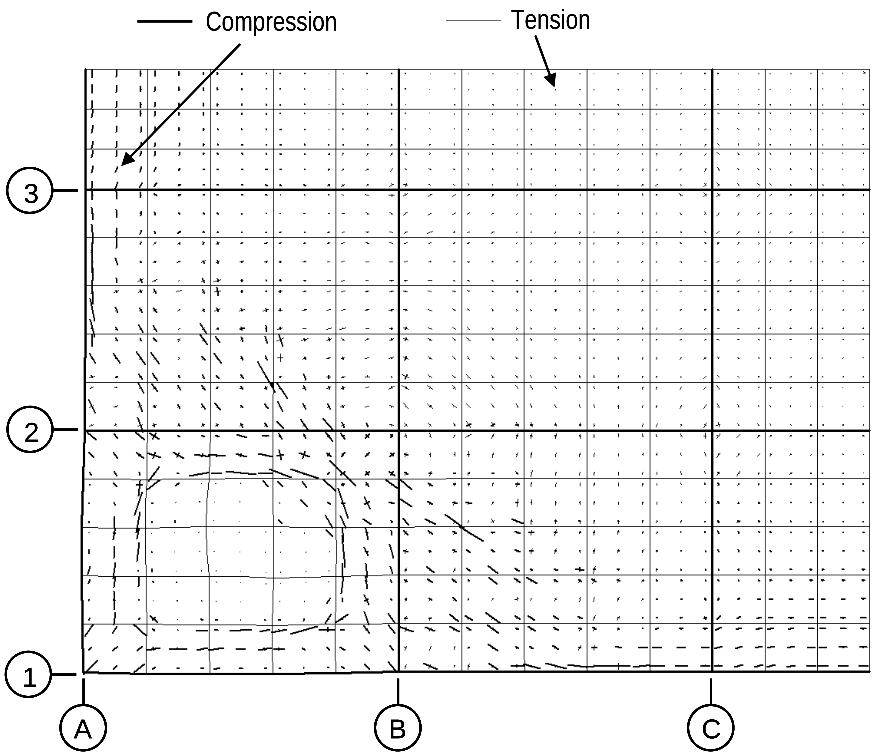

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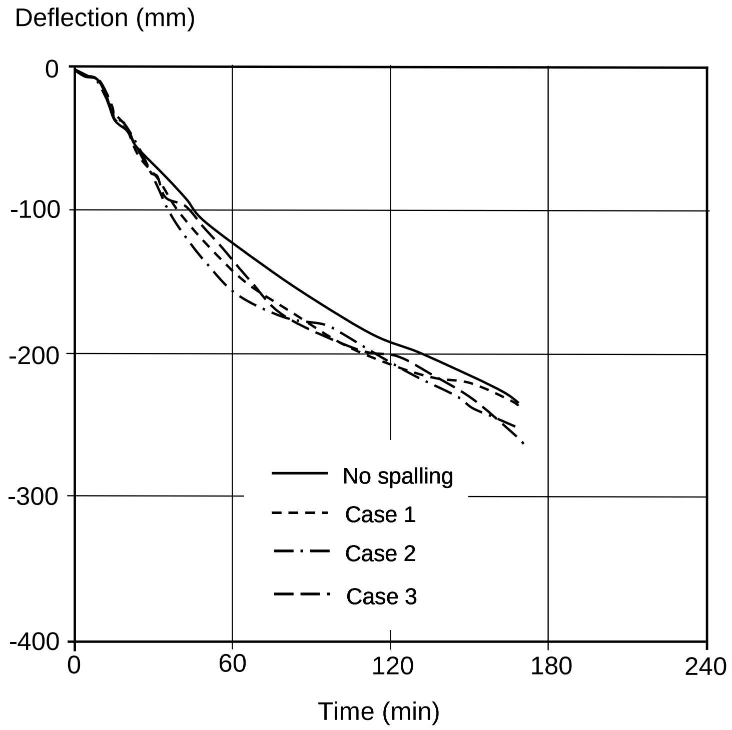

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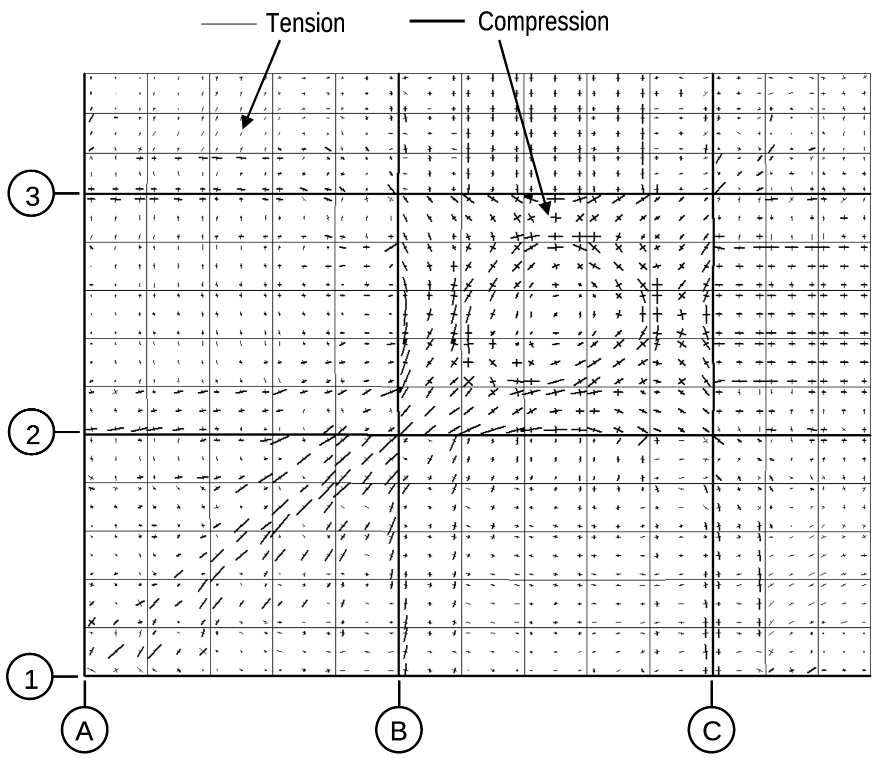

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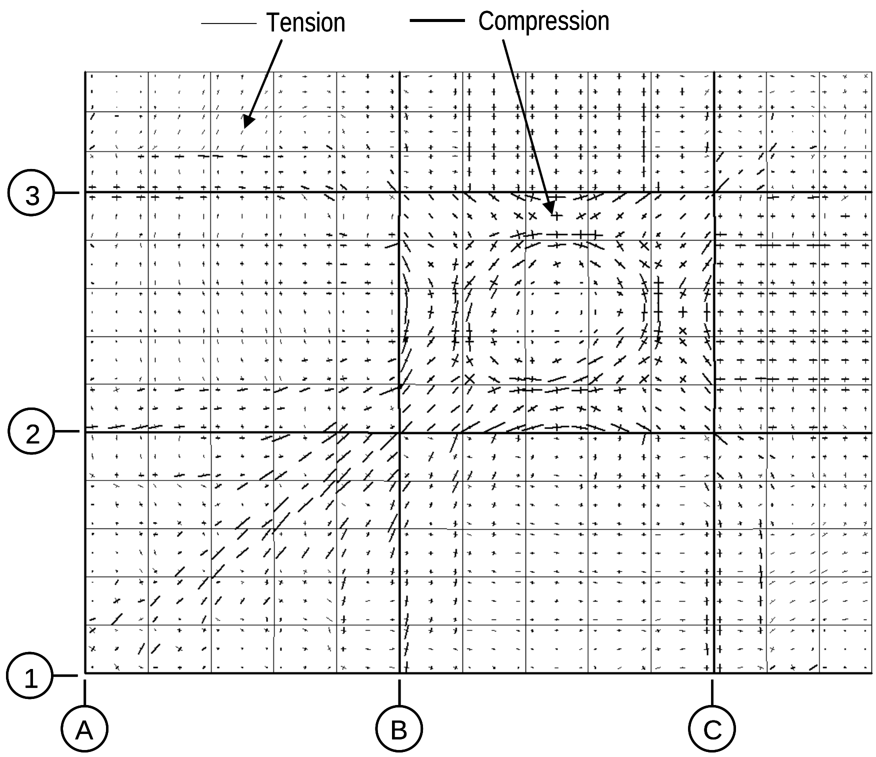

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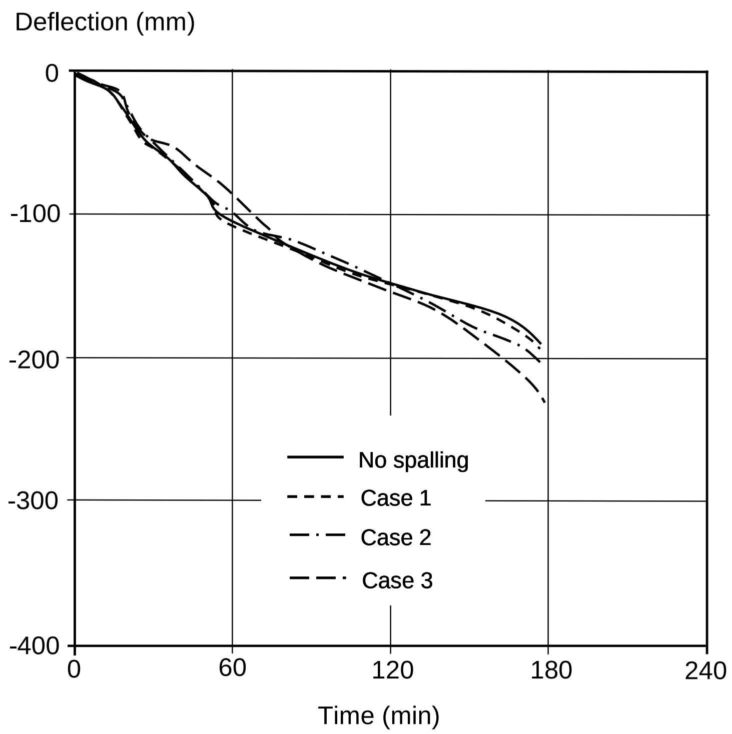

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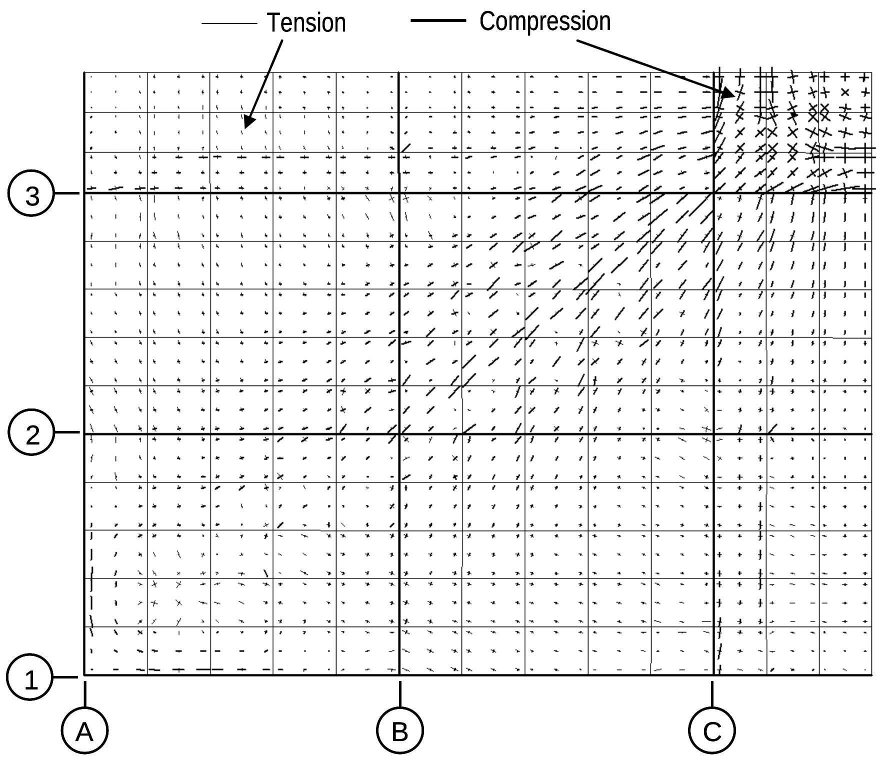

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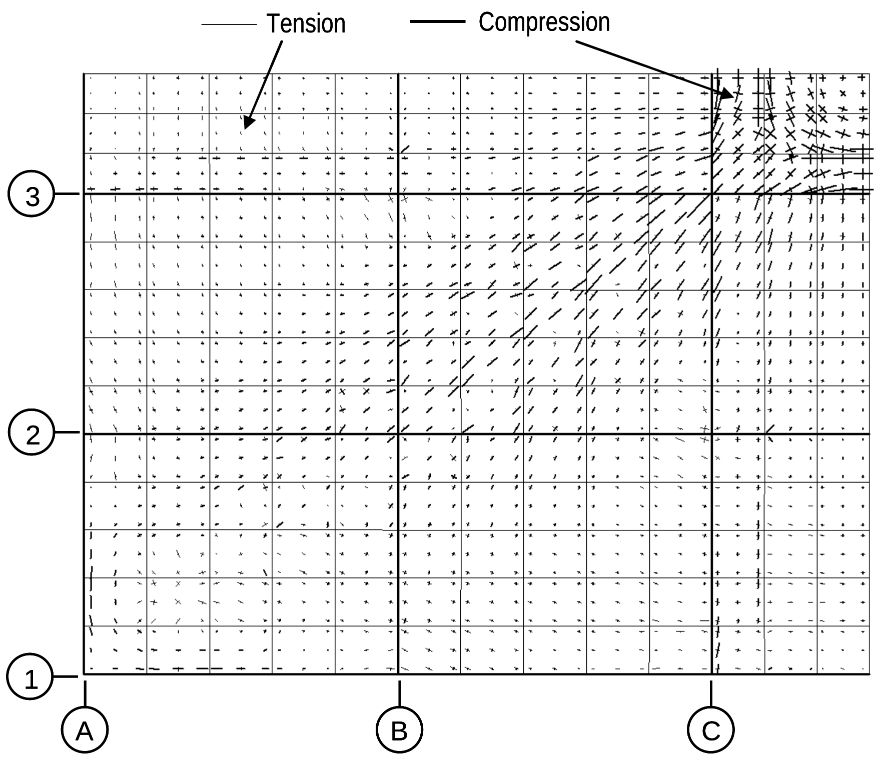

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