PIT Project Research Report: SM5
FEAST Modelling of Tensile Membrane Action in the Cardington Test 1

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1 Abstract

Following the full-scale fire tests conducted at Cardington, there has been some discussion of the role of tensile membrane action in maintaining the integrity of structures under extreme fire conditions. This report explores the availability of tensile membrane action as a load carrying mechanism in heated composite steel-concrete structures. The strain pattern in the reinforcement at the end of the first Cardington test is contrasted with the pattern that would be developed if the compartment was loaded with a static load of ten times the magnitude used in the fire test, but not heated.

2 Introduction

A primary concern of fire safety engineering is to prevent the catastrophic collapse of structures due to fires. This aim is to ensure that the occupants of a building can escape safely if there is a fire, without being trapped by the building collapsing. Fire-fighters also need to be protected from such a possibility. In simple cases, such as determinate structures, the temperature at which a structure will collapse is determined by the degradation of material properties. Once the material of the structure is no longer capable of sustaining the stresses produced by the loads applied to it, collapse will occur. The situation is much more complex in redundant structures for two reasons. Firstly, alternative load paths exist that prevent collapse even if one element of the structure becomes overloaded. Secondly, and more importantly for structures in fire conditions, the redundancy may result in thermal expansion being restrained. This restraint results in loads being applied to the structure because of the heating. The effects of these additional loads, together with large deflections resulting from thermal expansion, is to produce many complex structural phenomena, some beneficial to structural integrity, some deleterious.

One load carrying mechanism available to heated structures is tensile membrane action. Tensile membrane action occurs when structural elements such as beams or slabs, cease to act as bending members and instead act in tension. For this change to take place the members need to be well restrained against horizontal displacement at their ends. In addition, significant geometric changes must take place in a structure before tensile action can be developed.

When concrete floor slabs, such as those used in the Cardington frame, develop tensile membrane action, only the reinforcement can be considered to give reliable tensile strength because the concrete will crack at very low strains. Consequently it is often held that tensile membrane action can only occur in slabs within a small deflection range. It is argued that if the deflections are too small then there is insufficient change in geometry for the tensile action to be developed and that if the deflections are too large then the tensile strains in the reinforcement will cause the steel to rupture. This argument is based around an understanding of structures at ambient temperature. The purpose of this report is to explore the effect of heating a compartment in a large redundant structure on the availability of tensile membrane action as a load carrying mechanism within the compartment.

To understand the effects that thermal expansion may have on the availability of tensile membrane action, it is vital to distinguish between thermal strains, mechanical strains and total strains. At ambient temperature total strains and mechanical strains are equal and so lead to both stresses and deflections. This is no longer the case in heated structures where strains are related according to the following equations:

$$\epsilon_t = \epsilon_m + \epsilon_T \tag{1}$$

$$\epsilon_T = \alpha \Delta T \tag{2}$$

$$\begin{aligned} \text{where } \epsilon_t &= \text{total strain} \\ \epsilon_m &= \text{mechanical strain} \\ \epsilon_T &= \text{thermal strain} \\ \Delta T &= \text{Temperature} \end{aligned}$$

It is still true that total strains lead to deflections but it is now mechanical strains that lead to stresses. That this is the case can be clearly demonstrated by considering the simple example of a uniformly heated fixed ended beam. As the beam is heated the thermal strains are completely cancelled out by mechanical strains of equal magnitude but opposite sign. The total strain and the deflections remain zero whilst stresses are induced as a result of the mechanical strain. If the fixed ends were now replaced with rollers the mechanical strains and hence the stresses would be zero. Meanwhile the total strains and deflections would increase. These ideas have important consequences when it comes to considering deflections in heated structures. It is no longer necessarily the case that large deflections imply large mechanical strains and so it is quite possible for tensile membrane action to occur at deflection levels which would result in rupture of the reinforcement at ambient temperature.

This report first examines to what extent tensile membrane action is present in the first of the Cardington tests.[1] This case is then contrasted with the case of the same compartment loaded with a purely static load but of magnitude of ten times that used in the fire test. The increased static load is applied over the same area of slab as the temperature load. These two case present an interesting contrast since both loading conditions result in high deflections. In the unheated case the increase in geometric length that results from large deflections must be entirely accommodated by mechanical strains. In the heated case this increase in length can be to some extent accommodated by thermal strains. The extent to which the thermal strains compensate for the increase in length determines when tensile membrane action becomes available. If the thermal strains are sufficient to accommodate large changes in geometry, it is possible that tensile membrane action does not occur until deflections are very high and may, as a result, be considered a load carrying mechanism "of last resort" for the structure.

The above effects are explored in this report with a numerical model of the compartment used in the first of the Cardington tests. The model of this compartment has been described in detail in report MD3.[3] The area of the test in relation to a typical floor of the building is shown in in Fig. 1 and the details of the area modelled are shown in Fig. 2. The FEAST[2,4,5] suite of programs, developed specifically for modelling heated concrete slabs, was used for the analyses in conjunction with the ABAQUS[6] commercial finite element package.

3 The Differences Between Static and Thermal Loading

The results for the thermal loading and static loading are presented in Figs. 3 to 6. It can be seen that the behaviour of the structure is very different under the two forms of load. Also, for both forms of load, the patterns of strain parallel and perpendicular to the ribs differ. The maximum deflection of the structure under temperature loading was about 250mm and under static loading about 95mm.

The most marked differences between the results for the heated and static cases occurs in the mechanical strains parallel to the secondary beams. In the heated case (Fig.3) reinforcement mechanical strains remain almost entirely in compression. The only exception being along the boundary of the heated compartment towards mid-span where small tensile mechanical strains are produced because of compatibility requirements between the heated and unheated regions. These tensile strains are below the yield point of the steel (c0.002). The predominance of compressive mechanical strains, despite deflections of the order of span/36, results from the enormous thermal expansion that is produced by almost the entire span being heated. At the end of the heating, 8000mm of reinforcement has been heated to a temperature of 383C. This would result in a free thermal expansion of around 40mm. The deflection at mid-span is around 250mm and so by crudely assuming that the slab deflects in the form of two right-angled triangles an increase in length of 14mm can be estimated - less than half the available thermal expansion. This simple calculation, together with the finite element analysis results show clearly that even at very large deflections a heated structure may be some way from developing tensile membrane action.

By contrast, the results for the mechanical strains parallel to the secondary beam for static loading (Fig. 6) show that the reinforcement has developed tensile strains that exceed the yield steel of the steel. It is also noticeable that whereas in the case of thermal loading the thermal expansion swamped the geometric effects, in the case of the static loading the effects of changing deflections and curvature on the mechanical strains are clearly apparent.

Both load cases produce tensile mechanical strains perpendicular to the heated joist and these are of comparable magnitudes (Figs. 4 and 6). However the overall strain pattern in the two cases is very different. For the static load the tensile strains result from the slab sagging between secondary joists - in the hogging regions over the joists the reinforcement is in compression. In the heated case tensile strains occur over the full width of the tested compartment near midspan and are largest over the tested joist. The strains in this case result almost entirely from changes in geometry. Near the column no tensile strains are present because the deflections here are small. In both cases the maximum tensile strains are around the yield strain of steel.

4 Conclusions

- Tensile membrane action occurs at higher deflections in heated structures than unheated structures.
- The magnitude of tensile strains in heated structures depends on the deflections and on the amount of thermal expansionin the direction of the strains.
- The tensile strains in the unheated load case would be likely to result in rupture of the reinforcement parallel to the secondary joists.
- Tensile membrane action was predicted numerically perpendicular to the secondary joist but at a level that would not result in rupture of the reinforcement. This prediction is supported by observations from the test.

References

[1] P.N.R. Bravery. Cardington Large Building Test Facility. Technical report, iki, c1993.

[2] M. Gillie. Modelling Heated Composite Floorslabs with ABAQUS using a UGENS subroutine. In *ABAQUS Users' Conference 2000*. Hibbett, Karlsson and Sorenson, INC, 2000.

[3] M. Gillie. PIT Project Research Report MD3: BS/TEST1 model using FEAST with shell elements. Technical report, University of Edinburgh, 2000.

[4] M. Gillie. PIT Project Research Report SS2: Development of generalised stress strain relationships for the concrete slab in shell models. Technical report, University of Edinburgh, 2000.

[5] M. Gillie, A.S. Usmani, and J.M. Rotter. Modelling of Heated Composite Floor Slabs with Reference to the Cardington Experiments. *Fire Safety Journal*, 2000. accepted.

[6] Hibbet, Karlson and Sorenson, Providence, Rhode Island, USA. *ABAQUS Users' Manual, Vols I to III, Ver 5.8*, 1998.

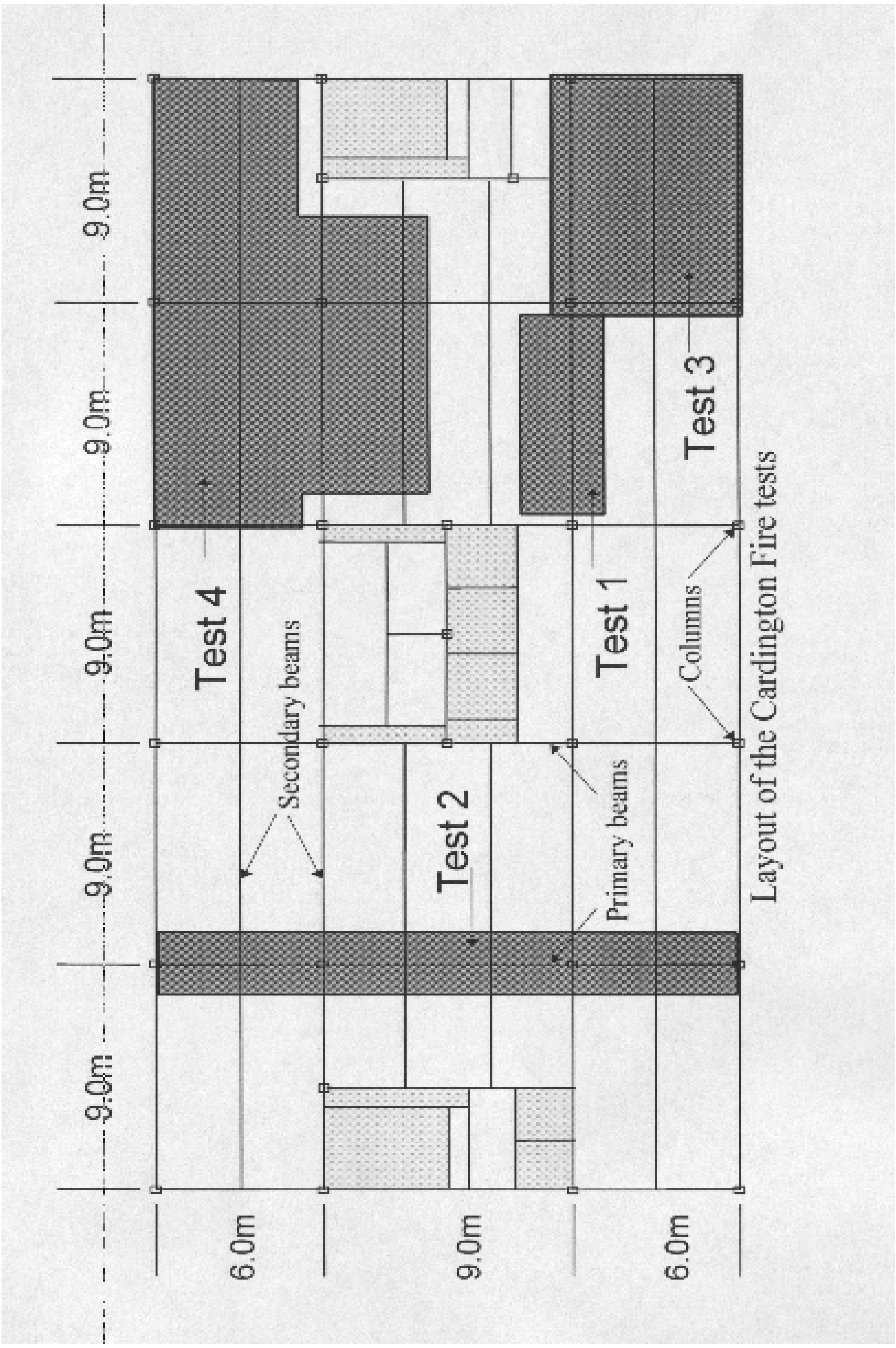

Figure 1: Layout of a typical floor of the Cardington frame showing the locations of the various tests. It should be noted that each test was carried out on a separate floor.

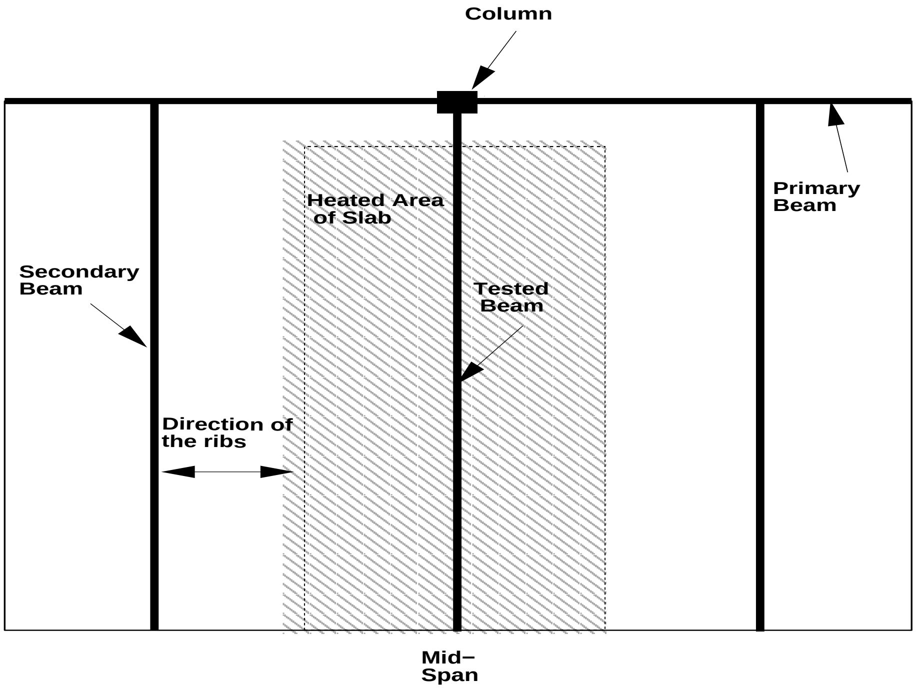

Figure 2: Schematic plan view of the area of the Cardington frame modelled for the analysis of test 1.

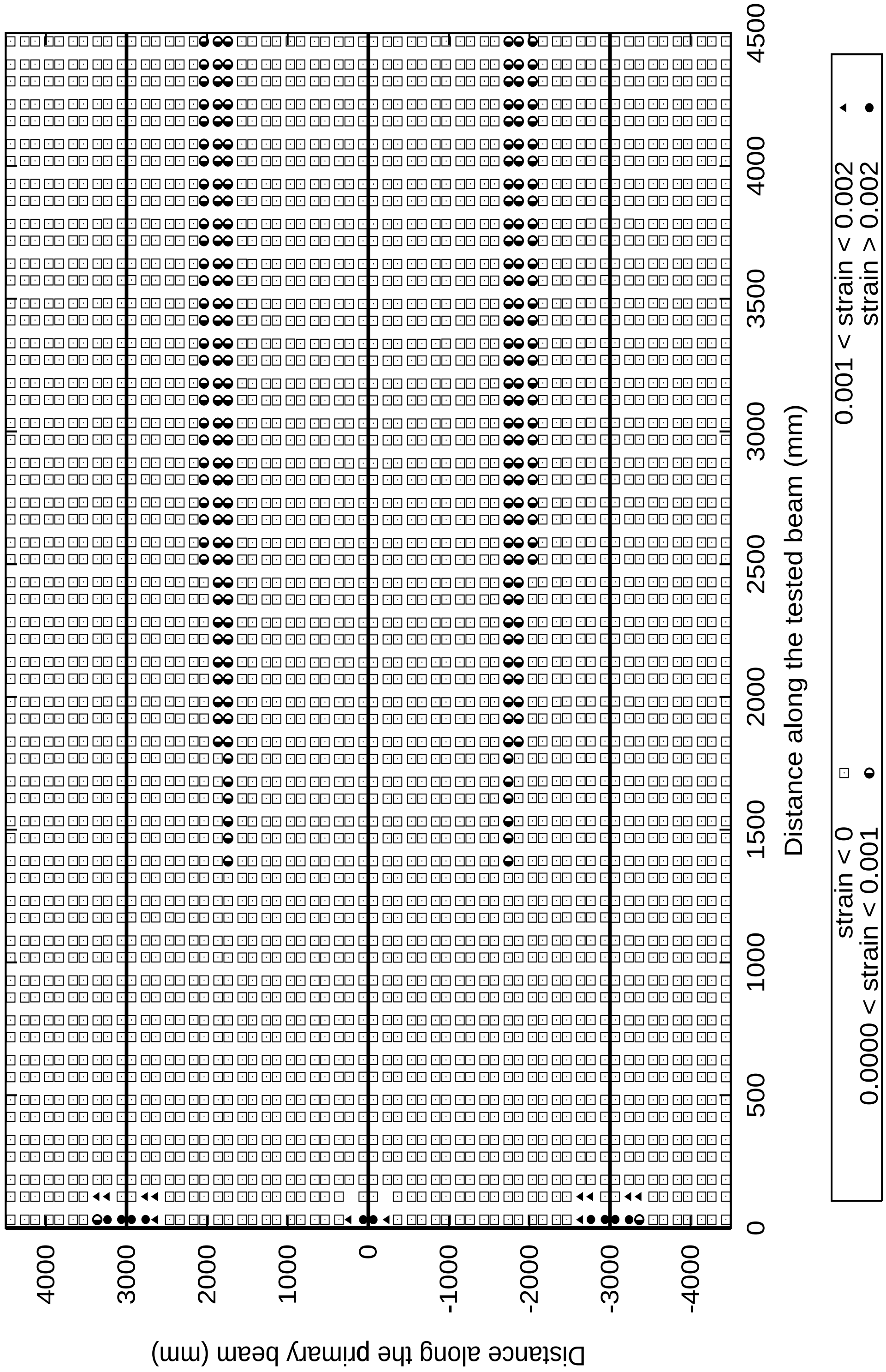

Figure 3: Reinforcement mechanical strains at the end of test 1 in the x-direction

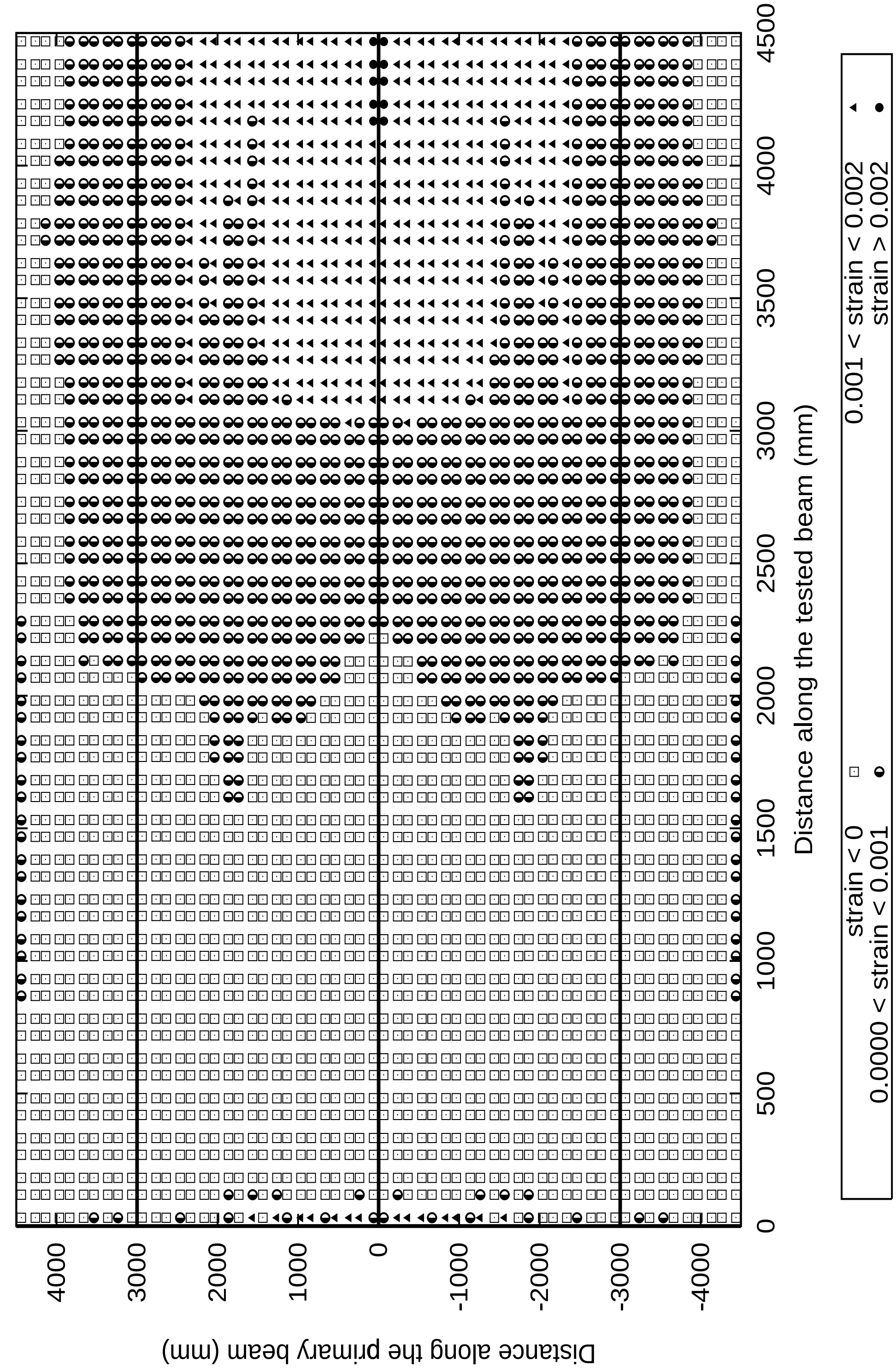

Figure 4: Reinforcement mechanical strains at the end of test 1 in the y-direction

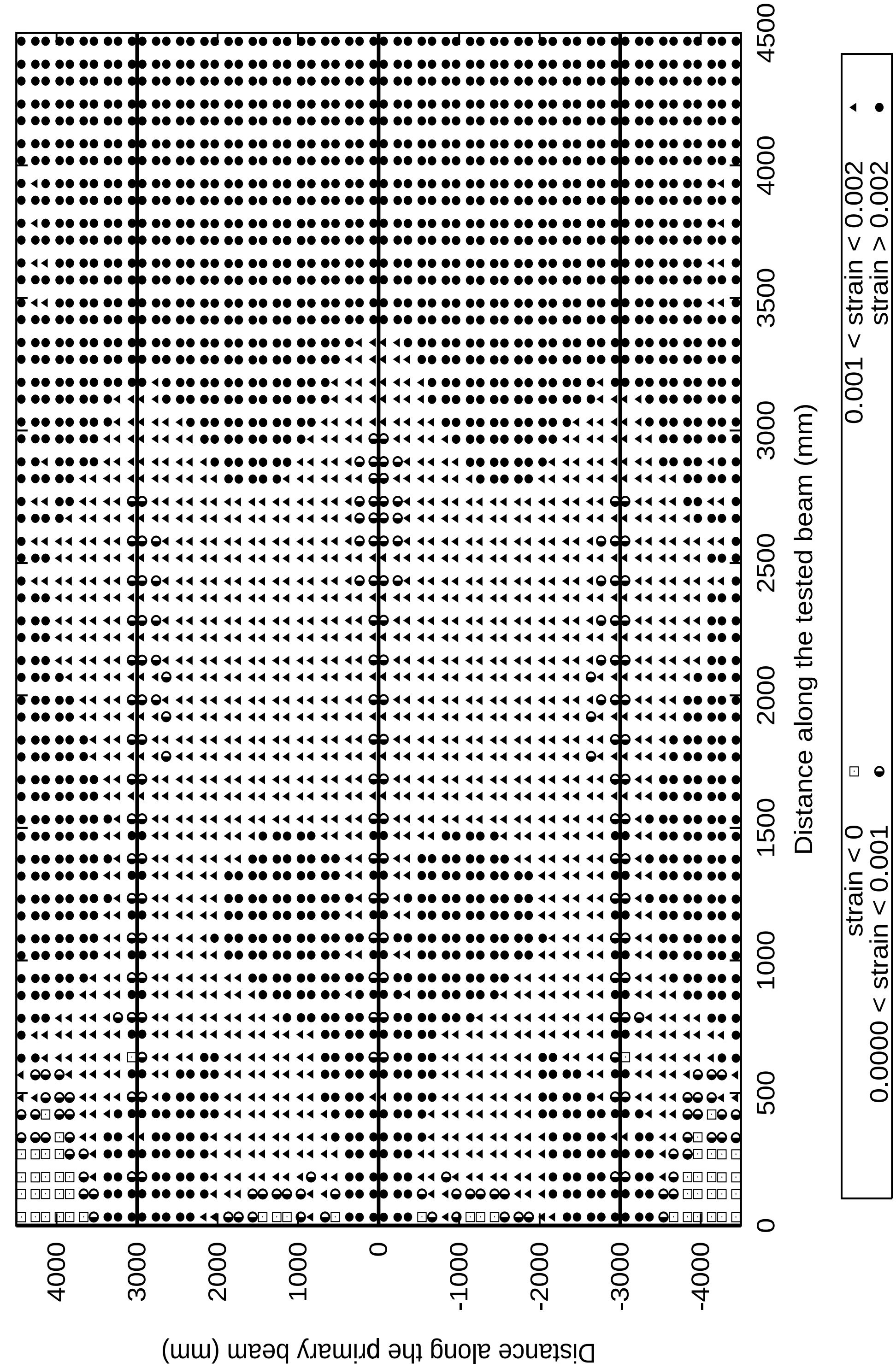

Figure 5: Reinforcement mechanical strains under a load of $0.05 N/mm^2$ x-direction

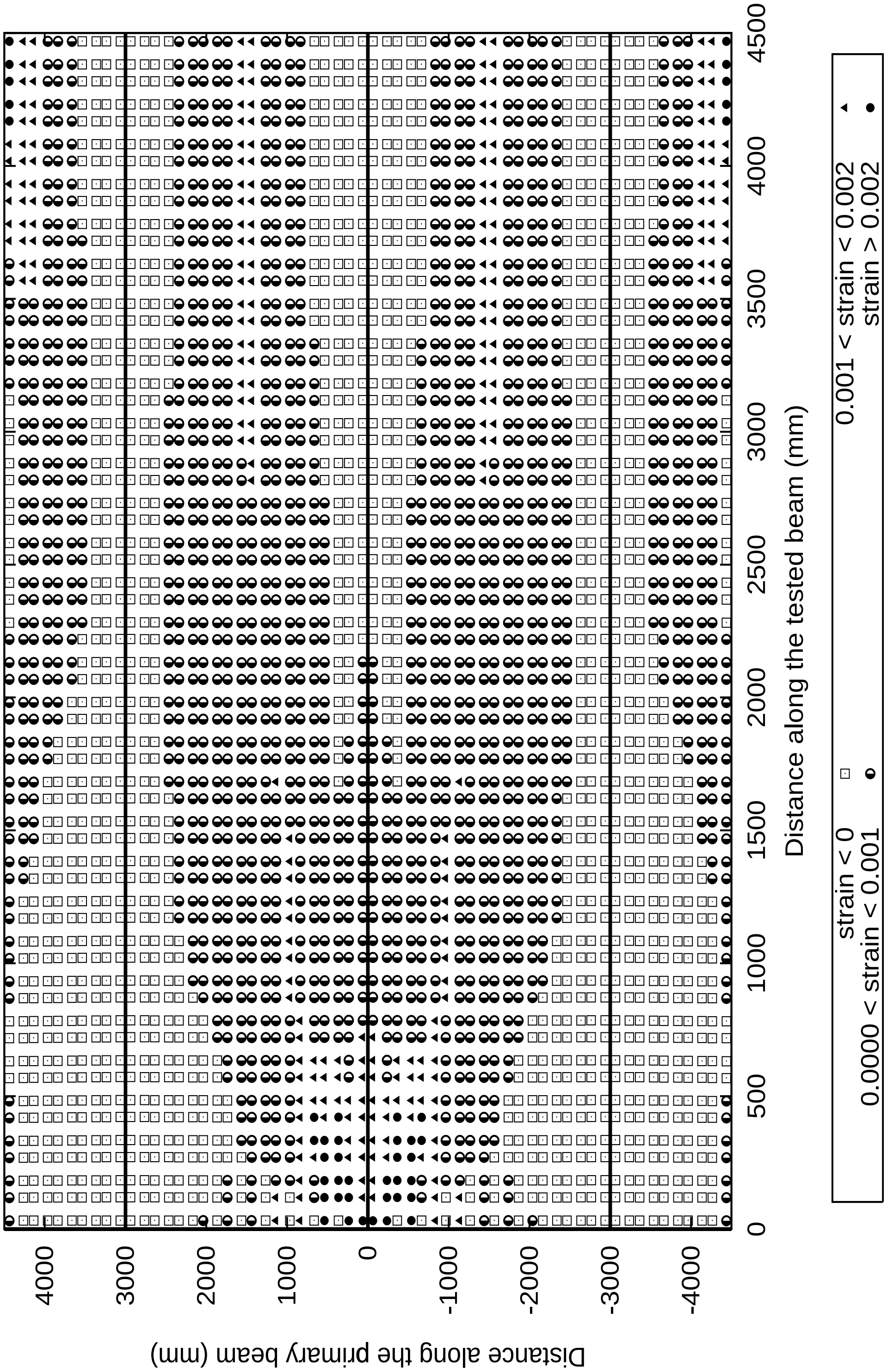

Figure 6: Reinforcement mechanical strains under a load of $0.05N/mm^2$ y-direction