The strengthening of the West Tower of Ely Cathedral

J. HEYMAN

Mr D. W. Smith, University of Dundee; Consultant, Mott, Hay & Anderson

How did they do it without modern equipment? How did they know how, without modern structural analysis? These are the questions that perpetually puzzle today's engineers when they think of the staggering achievements of mediaeval cathedral builders. Professor Heyman had no space in this excellent and crowded Paper to do more than whet the appetite on these irrelevant but intriguing questions; hopefully he will give his thoughts on them on another occasion.

98. It would be interesting to have more information on the stainless steel cables: the diameter and properties of the wires and of the core, the length of lay, and the duration and results of the laboratory measurements of creep.

99. It seems likely that more than half the elastic extension was due to the squashable nature of the low-modulus core. Are there grounds for supposing that the material of the core will keep its mechanical properties over a long period of years? Is it possible that the core's properties will be time-dependent in a manner that cannot be shown up by a short-term creep test?

100. It is usual experience with bridge ropes, single strand, long lay, and with no softer material than a thin layer of zinc on the surface of the wires, that they continue to stretch slowly for a very long time, in defiance of experimental proof of stable conditions after the most careful removal of non-recoverable extension on the pre-stretching bed.

101. No doubt at Ely it would be a simple matter to retension the cables after a few years if this should prove to be necessary, but Professor Heyman's comments on these points would be most useful.

Mr J. F. S. Pryke, John F. S. Pryke and Partners

Professor Heyman's Paper will be a most helpful reference for persons concerned with maintaining old buildings. In particular I note his advice to 'leave well alone' in § 35 and the principles given in § 36. These principles serve to reinforce the advice of experienced conservators that continuing and regular maintenance is the key to retaining historic buildings. Nowhere is 'a stitch in time' more relevant.

103. I would be grateful if Professor Heyman would comment on two points. In § 29 he says that the engineer must ensure that the force system will 'lie within the masonry'. For highly stressed areas, that is for average compressive stresses up to 0.1 times the crushing stress of the masonry, the lines of action must presumably lie comfortably within the masonry, say more than $b/10$ from a face where b is the masonry thickness in the plane and at the position being considered. For comparison the familiar elastic theory would indicate $b/3$ for rectangular sections. For nominally stressed sections would Professor Heyman recommend $b/20$, for example?

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104. The other point upon which I would appreciate comment is the decision to grout with 'neat cement' recorded in § 43. This grout will have shrunk when setting and will have filled the voids in the grouted zones with veins of material much harder and more brittle than the stone and mortar being grouted. Was consideration given to a softer grout more compatible with the original mortar?

Dr R. J. Mainstone, Building Research Establishment

Professor Heyman has clearly left the West Tower at Ely a stronger and safer structure than he found it. With modern techniques at his disposal he has been able to improve considerably on Scott's earlier remedial works. But it is much less clear how and why he decided on the precise measures adopted. This is not clear from §§ 20-36. Or, if it is, these paragraphs suggest that the right things may have been done for the wrong reasons.

106. Of the principles summarized in § 36, (b) and (c) are, surely, self evident. But (a) seems to be neither self evident nor validly established by the arguments of §§ 20-28. Whatever it may be convenient or necessary to assume in applying plastic theory to masonry structures, loads on columns will actually be distributed between skin and fill in accordance with their relative stiffnesses. A relatively weak and easily compressible fill will carry virtually no load. Indeed there is ample evidence that highly non-uniform stresses exist even in a typical skin on account of the variable thicknesses of mortar joints and the greater compressibility of mortar as compared with the facing stone. It would therefore be more correct to state as the first principle that weak masonry or loose rubble infill should be consolidated or renewed to such an extent as is necessary to give the essential elements of the structure adequate strengths and stiffnesses. This leaves open for consideration in each particular case the desirable consolidation of loose infills.

107. As a more precise guide to appropriate action, I would suggest that the engineer would do better to envisage in as much detail as possible how the structure may fail, than to ask how he should modify it to make it conform to a preconceived theory of structural action as suggested in § 27. The well documented collapse of the tower at Chichester referred to in § 35 is instructive here.⁷ A loose fill threw the load on the skins of the crossing piers. Local high stresses then resulted in local splitting of the skin masonry. Finally, under the combined action of vertical load and the outward pressures exerted by the loose fill, parts of the skin bulged and buckled and precipitated complete collapse of two of the piers and the partial collapse of the other two.

108. From the evidence presented in the Paper it appears that the ultimate collapse of the West Tower at Ely would have taken place in a broadly similar manner. If so, I suggest that the forestalling of such a collapse is the real justification for the stitching and grouting as well as for the tie bars and cable ties. Because it is discontinuous vertically it is very difficult to see how the grouting can have led to the fill taking over any significant part of the vertical loads. (Vertically continuous grouting might also have resulted in little direct sharing of vertical load, but would have made a valuable contribution to overall strength and stiffness by stiffening the fill and preventing it from exerting a progressive outward pressure on the skin. It might, therefore, have been considered as an alternative, either with reduced stitching or without any.)

109. More generally I have come to the conclusion (from detailed study of a good number of past failures) that vaulted masonry structures usually collapse as a result of an initial buckling type of instability. Deflexions under non-uniform and eccentric compressions gradually increase as a result of creep, weakening of materials, and the slow but inevitable progressive growth of cracks and slips until the compressions somewhere become too eccentric and 'geometric stability' is lost. The mechanism demonstrated at Chichester was just one example of this. As stated in § 25, plastic theory has to assume that deflexions remain small. For this reason I have always seen its relevance to masonry structures as being very limited. Hitherto, however, Professor Heyman and I have argued this point only at an academic level. My greatest regret in reading the present Paper is that he has not shown more clearly and convincingly that the theory has some practical relevance. If it did assist him in determining the number, size and

placing of the new stitching bars and tie rods and cables, I hope that he will be more explicit about this in his reply.

Dr M. S. Gregory, University of Tasmania

I congratulate the Author on the careful work done at Ely and on his lucid Paper. It is pleasing to read how engineering science and craftsmanship were combined to restore the tower. As a former contractor's tunnel engineer, I rather relish Professor Heyman's remarks that a pneumatic drill can be a precision instrument and grouting a craft.

111. I agree in the main with the structural principles enunciated in §§ 20–36 with only minor reservations. Safety can never be an absolute matter, it seems to me: there is always some set of circumstances which will cause a structure to fail. The safety of the structure hinges on the two words 'no danger', in the last sentence of § 20, and the responsibility for this decision must rest with the designer or engineer, as indeed Professor Heyman has pointed out. The name 'safe theorem' is a very suitable one; I prefer to state it along the following lines: if, for a given set of loads, a thrust line can be drawn through a masonry or stonework structure (using the principles of statical equilibrium) in such a way that the designer is sure there will be no crushing, then he has a lower bound on the collapse load. Provided he has done his work properly, and taken into account movements of the structure or its foundations if they are likely to occur at that loading, then the structure will not collapse under that loading. But that loading is not an absolutely safe one: the designer must set a suitable margin between his structure and its collapse. He cannot avoid having to ask himself, 'How close to collapse is this structure for the loading and other conditions for which I drew this set of thrust lines?' This very question is being asked in Tasmania now for some of our masonry-arch railway bridges over which it is proposed to run heavier locomotives than ever before.

112. The above considerations are, however, no more than another way of putting Professor Heyman's conclusions (§ 30–31): the engineer seeks compressive force in such structures, shape is all important, and the geometry must be stabilized. It is generally best to leave well alone. A good deal of the cracking which occurs is no cause for worry; the structure has found or is finding a suitable thrust configuration.

Professor Heyman.

Mr Smith asks how it was done! I can only answer that we know some of it, but that perhaps we shall never recover all the lost secrets. As to *what* was done, Viollet-le-Duc's ten-volume *Dictionnaire*⁸ is a never-failing source of information. (It is a matter of regret that G. G. Scott, who restored Ely and who was perhaps more active in England than Viollet-le-Duc in France, left correspondingly a much smaller record of his experience. Almost inevitably, it was Scott who restored the tower and spire of Chichester, whose fall was mentioned in the Paper, and to which Dr Mainstone alludes.)

114. As to the secrets, some of these are uncovered to those who can survive a reading of Frankl's massive study⁹ of Gothic. Frankl makes it clear that the rules preserved in the mason's Lodges concerned proportion; they were numerical rules, rules of geometry, and the principle of § 36(b), that geometry should be stabilized, lies centrally in this mediaeval tradition.

115. As to *how* it was done, Viollet-le-Duc helps and Ungewitter¹⁰ contributes incontrovertible evidence; but the most complete study of constructional techniques has been made by Fitchen.¹¹ Some of Fitchen's tentative conclusions can be criticized, but there is nothing better as an introduction to the understanding of how cathedrals were built.

116. Mr Smith also asks a specific question about the cables in the belfry. It is indeed possible that there may be some slow continuing relaxation of tension in the cables; they are accessible, and can be retightened if necessary. They are at the moment stable on a time-scale of months, but perhaps not of years. As an example of one of the laboratory tests, a cable was tensioned to 2.60 tons (the working value), and was observed to have relaxed to 2.50 tons after an hour; two days later the tension was 2.37

tons. The cable was then retightened to 2.58 tons, and had relaxed to 2.55 tons after a further 24 hours. As mentioned in the Paper (§ 67), the eight cables installed in the belfry had apparently stabilized after four weeks.

117. Mr Pryke asks, by implication, about factors of safety. If mean stresses are 10% of the crushing strength of the material, how close can the line of thrust approach to the surface of the masonry? It is illuminating, in studying the stability of masonry arches,¹² to define a 'geometrical' factor of safety, rather than a safety factor on stress. The structure is imagined to be 'shrunk down' uniformly towards its centre lines, becoming more and more attenuated, until the thrust lines can no longer be accommodated within the masonry; the ratio of the dimensions of the original to the attenuated structure gives some measure of the stability of the construction. Such a factor is certainly of more importance in masonry construction than 'middle-third' rules, or rules of 'b/20', for example.

118. This is something that Dr Mainstone seems unable to accept; further, it appears that he cannot appreciate that the plastic theorems provide the key to the understanding of the behaviour of masonry. He concentrates on symptoms, rather than causes; his reproduction of Willis's account of the fall of the tower at Chichester is an account of the death-bed throes, not an aetiology of the disease. Willis himself, as an architectural historian, gives a careful account of the collapse; as an engineer, however (and Willis was the primogenitor of the engineering school at Cambridge), he prefaces his particular report with a more general survey of the potential weaknesses of masonry construction.

119. The tower at Chichester probably fell because of weakness in the crossing piers. There seems to be little wrong with the main piers at Ely (§ 40), and Dr Mainstone's remarks are misdirected. The grouting of loose infill at Ely was done in places where the vertical stresses are very small; the purpose of the grouting was to help in the formation of horizontal 'reinforced concrete' ring beams (§ 45), not to carry vertical loads. Thus, in answer to Mr Pryke, strong grout was used, rather than a weaker 'matching' mortar.

120. The arguments leading to the formulation of the principles of the restoration may or may not be clear. However, in § 32 it was stated that the principles may appear so self-evident as to be slightly absurd, and it is rather hard in these circumstances to be told by Dr Mainstone that two of the principles are self-evident, while he attacks the third on irrelevant grounds.

121. Of course, changes in geometry must be taken into account, as is implied in § 36(c), but Willis himself was certain 'that settlements and disruptions . . . may be seen in many buildings, that exhibit no alarming symptoms of actual ruin'. This certainly stemmed from Willis's deep understanding of the behaviour of masonry, an understanding that is now buttressed by the plastic theorems. Of these, the lower-bound, or 'safe', theorem is fundamental, as noted by Dr Gregory.

122. Plastic theory, of which Dr Mainstone is so suspicious, cannot be expected to give complete answers to every question. The lower bound theorem does, however, place a powerful tool in the hands of the engineer. It is, perhaps, something like money—as in the phrase 'money isn't everything'. The lower bound theorem is not everything either; but it helps.

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