Paper No. 5177.

"An Experimental Study of the Voussoir Arch." †

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Professor R. V. Southwell thought that the most striking feature of the Paper was the close agreement of its theory with the experimental curve F in *Fig. 9* (p. 895 §), especially when consideration was given to observation (7), p. 400 §.

If the voussoirs could be treated as rigid and indefinitely strong, then (as had been already shown *) a statical theory, on the basis of mechanical instability occurring in what was effectively a four-bar chain, would be adequate. There would seem to be little doubt that a theory of that kind served to explain all the essential features of the problem, but it should be remembered that such a theory presumed a knowledge of the points at which "hinging" could occur. That knowledge was available on the understanding that the voussoirs were rigid and had plane faces: "hinging" could then occur only at the extrados or at the intrados. If, however, a procedure were adopted such as the insertion of pads between adjacent voussoirs, then "hinging" could be made to occur anywhere. If such pads were soft and of some extent, then it was certain that the effective hinge would, in every case, lie at some point between the intrados and extrados. If a soft rubber pad were fitted over the whole plane face of the voussoir, then, as instability approached, the stress in the rubber would be either zero or compressive, with a maximum at the face of the arch; the effective hinge would again lie between the intrados and extrados, since the rubber would not permit line-contact between voussoirs. If, furthermore, it were assumed that the rubber could only sustain a limited stress without failure, then, as instability approached, there would be a further circumstance making for an inward movement of the hinge; a finite depth of hinge would be necessary, given by the quotient of twice the thrust by that limiting stress. That was on the assumption of a linear distribution of stress across the depth of the pad, and, on the same under-

† Journal Inst. C.E., vol. 10 (1938–39), p. 383 (January 1939).

§ Page numbers so marked refer to the Paper. (Footnote (†) above.)—SEC. INST. C.E.

* A. J. S. Pippard, E. Tranter, and L. Chitty, "The Mechanics of the Voussoir Arch." Journal Inst. C.E., vol. 4 (1936–37), p. 281 (December 1936). *Discussion in* Journal Inst. C.E., vol. 6 (1936–37), p. 5 (June 1937).

standing, the effective hinge would lie at one-third of that depth from the heavily-loaded edge. When the problem was visualized in that way, it seemed clear that finite strength would entail an inward displacement of the hinge, becoming greater as the thrust increased; that in turn would entail instability at a lower load than before.

Assuming a figure for the limiting stress, it would appear possible to give that argument quantitative form and to calculate the load at which mechanical instability would occur. Professor Southwell suggested that the converse calculation should be attempted, to see whether the results of *Fig. 9* (p. 395 §) were consistent with some reasonably uniform strength-value for the lime-mortar, and if so, what that value would be. It would be highly satisfactory if the result should emerge that *Fig. 9* could have been predicted on the basis that a definite limit to the crushing strength of the mortar implied a definite inward movement of the hinge when subjected to a given thrust; for then (because the inward movement increased with the thrust) there would again be a definite stability-limit which would, however, be less than that calculated on the assumption that the voussoirs had infinite strength and touched one another directly.

The Authors, in reply, observed that the point raised by Professor Southwell had been considered in some detail, and there was little doubt that if the jointing were formed of a material whose elastic properties were definite it would be possible to calculate, with very good accuracy, the real position of the pins. A small model-arch had actually been made in which the jointing material was replaced by rubber pads whose positions could be varied, but it had not been considered worth while to carry that work very far. When the original research had been planned it had been intended to carry out some tests with rubber pads about $\frac{1}{4}$ inch thick replacing the mortar joints, but unfortunately that set of experiments had not been done.

The arch was, however, still available, and it might be possible during the course of next year to complete the original programme and to throw further light on the location of the "pins" in the joints under the conditions suggested by Professor Southwell.

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§ *Ibid.*