WHERE TO FROM HERE?

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Abstract: Twentieth century researchers responded to the need to produce a 'plastic' building material based on concrete. In the twenty first century the search should be for potentially superior building technologies that are less burdensome on the environment. The destruction of the Twin Towers in 2001 calls into question some current construction practices. Integration of construction teaching alongside theory and design is overdue. This leads to the question, 'Where to from here?'

1 INTRODUCTION

Christopher T. Morley has made his mark in concrete plasticity studies: he has left his signature on the field. This is consistent with one of the meanings of the word 'morley': as defined in the Oxford English Dictionary to be 'a signature, or a person's handwriting'. It is a rare privilege to be contributing to a retirement function for an esteemed colleague: it is very special! We first met in the Michaelmas Term 1963. CTM was working on his research thesis, supervised by R.P. Johnson. His thesis, 'The Ultimate Bending Strength of Reinforced Concrete Slabs', was submitted in 1965. It was a very highly regarded piece of research. Several important publications resulted. His undergraduate career had been exceptional. He was awarded all the relevant prizes in the gift of the Engineering Department.

A primary Engineering Departmental research interest at the time was the plastic steel framework researches lead by (Lord) John F. Baker (1901-1985). That programme in 1963 was then of more than twenty years duration. All sorts of unexpected things were happening. Most notable of the world events in those first few weeks of the new academic year was the assassination of President Kennedy in late November 1963. Much flowed from this violent event. Not for the first time the question was 'Where to from here?'.

2 NOTES ON THE RESEARCH ENVIRONMENT IN THE 1960'S.

In 1963 there were important happenings in the Engineering Faculty. The Baker Era was drawing to a close and new directions were opening up. Faculty meetings often turned out to be somewhat confrontational. The traditional divisions were being questioned. Salvos were fired at those who dared to introduce new options and, soon to follow, new Triposes, most notably in Electrical Sciences. This was serious stuff for staff to take on board, especially if they were new to Cambridge.

The plastic framework studies were brought to Cambridge by John Baker when he moved back to Cambridge from Bristol to fill the vacant mechanical sciences chair in 1943. The flowering of those ideas was quite rapid, especially in the 1950's. Plasticity studies relating to concrete started to gain momentum in the 1960's. Our esteemed colleague CTM was one of the local pioneers in this new sphere of structural mechanics.

Novel ideas were being encountered. They were exciting times. A pioneer paper [1] arising from the Morley thesis appeared in 1966 and remains of value to this day. The topic was minimum reinforcement for a concrete slab in a plastic collapse state. The example solved was the simply supported square shape. This paper was followed by many others, often with reference made to the Morley paper. Despite many attractive features, the body of optimisation theory and practice that has been built up by a small army of workers of diverse origins over forty years, has never achieved mainstream status. Its time may yet come!

Another worker in British structural concrete technology at that time was Randal H. Wood (1913-1987). His 1961 published book, *Plastic and Elastic Plates and Slabs* [2], was thought provoking and more influential than can be easily gauged from the literature. Wood notes his own interest in the studies of two then well known academics, the Danish yield-line pioneer K.W. Johansen [3], and W. Prager [4], then of Brown University in the USA. Wood was not an academic. He was a structural engineer employed in the civil service at the Building Research Station of the then DSIR. The evidence seems to be that Wood's book had been carefully studied by CTM. The same no doubt was true of Johansen's and Prager's writings. Another contributor was Eustace N. Fox. His Phil. Trans. papers on plastic plate bending, completed not long before he retired, remain as benchmarks in the subject [5] since they are some of the very few exact solutions for square yield locus plate problems and strengthen the numerous upper bounds on collapse loads.

From the 1920's and for the next 50 years the Cement and Concrete Association, a private sector research oriented body that had been built up by the cement manufacturers between the world wars, sponsored many studies of concrete as a structural material. The blue covered volumes in their 'Concrete Series' with the imprint 'Concrete Publications Ltd.', were much used and influential, especially in the construction industry. Prestressed concrete had been a central study during the post WW2 rebuilding of war damaged cities and infrastructure. The interest in 'concrete plasticity' was mostly academically driven, and came to fruition as the 'C&CA' was down-sizing. As had happened with steel, ductile (plastic) response was sought in the concrete structures built. CTM has been a consistent trend setter in this extending of the capabilities of structural concrete.

3 A WATERSHED EVENT.

What lessons have we learned from the collapse of the Twin Towers from a structural engineering perspective? The enormity of the event is undoubted: the 'experimental' data captured from this world-changing event is very meagre. It would be difficult to over-estimate the grave nature of the various fall-outs from the collapses. There are those who believe the Towers should not have collapsed. Another view is that the Towers were uniquely vulnerable structures. These are very uncomfortable views to hold. Collapse could only have been prevented if the fire protection systems had functioned as intended. But they did not. How safe then were the buildings? This remains an open question and a very sensitive one, since it touches a nerve in the American psyche. With so much of the basic data missing no definitive answers are ever likely to be arrived at as to their inherent safety.

In the months following 11th September 2001 many documentaries were screened around the world putting various emphases on the collapses. The official report, FEMA 403 [6], was published in September 2002. This is an excellent document. Thousands of pages of other reports have appeared since. But large gaps in basic knowledge remain. In recent days there have been reports of cancer-like illnesses now appearing that can be directly related to the collapses.

The choice of structural type for the Towers reputedly resulted from the client pressure to minimise the construction cost and maximise the speed of construction. The most fateful decision was probably the choice of trusses acting in a sort of composite with the lightweight concrete floors, plus the manner in which these elements were supported at the facade and the interior core. The original clients were also the certifying body responsible for approvals. Many features of the project were unusual and had a bearing on the collapses. It appears no one in authority during critical minutes anticipated building collapse as a probable outcome. Should they have? Had they the casualties would surely have been many fewer.

Conventional Risk Analysis assigned a minimal risk to such an outcome. Post '9/11' the insurance companies have changed their attitude to risk. Premiums have risen and there is increased conservatism towards new building technologies being introduced. But new technology must be explored if progress is to be achieved [7]. A positive consequence of the collapses is an increased interest in fire engineering strategies. Additional resources are being applied to fund new academic posts [8]. A symptomatic aspect of this need to re-educate shows up where, for example, a recent book reviewer [9] projects the notion that the structural steel in a building is likely to melt in a fire of the '9/11' character when the evidence is that the collapse occurs well before melting conditions could arise [6]. The same review includes an inaccurate account of the precursor event: the aircraft crash into the Empire State Building in 1945. That aircraft was not a 'small fighter' but a B25 bomber. There were fourteen and not just two deaths, and most were due to the resulting fire. No doubt the death toll would have been much greater had it not been a Saturday with the building nearly empty of staff. As happened in the '9/11' attack, substantial pieces of plane wreckage passed right through the building and fell into the surrounding streets, despite the forest of columns in the ESB. There was limited building damage. It was open for business in the following week.

4 CONCRETE TECHNOLOGY IN THE TWENTY FIRST CENTURY?

Concrete of itself is not a plastic material. The aim of the plasticity studies has been to ensure that concrete structures do exhibit the properties of material plasticity. This quality, also described as ductility, ensures there is no (immediate) loss of strength as the members are deformed beyond their elastic regime. To further this aim we need to focus on construction methods. The serious study of construction method as an academic discipline has not taken root, at least not in the English speaking world. There is good reason to elevate construction to the same level of intellectual inquiry as theory and design. Each has features to complement the others and these cannot be all fully developed in isolation. The total package for study under 'construction' should include devising methods that promote worker safety on site, the effects of the building process on the community at large, as well as all the cost effectiveness, quality etc. Temporary works are often the source of injury and deaths on site. The method of construction should call for as little as possible of temporary works to achieve the finished structure. Transport of heavy and often unwieldy components through city streets, large precast elements as an example, should be avoided if better alternatives can be demonstrated. Present day concrete technology is replete with examples of these and other potentially hazardous and often waste producing practises. The technology of the future will also need to achieve less environmental impact, when creating the structures, during their useful lifetime and beyond. Modern industry favours sub-contracting rather than in-house skilling. This has an impact on the fate of new technologies. There is much scope for thought, for the education process, for innovation and for producing benefit to society.

Generally we can achieve ductility through careful use of (steel) reinforcing. For about a century and a half most reinforcement has been provided as steel bar. Are there other means to provide the desired ductility that contribute to lessening environmental impacts? The post 9/11 environment has made it more difficult for new technology to enter the construction scene. Traditionally the industry has been portrayed as resistant to change [10]. There are alternative systems which aim to meet the above additional construction related criteria. One is to use *external reinforcement*. The material obtained when combined with concrete has been described as Externally Reinforced Concrete, or ERC. It is not suggested that such a system is superior to present day practices, only that this and other systems are worthy of study. The aim in ERC is to provide the reinforcement requirements as a 'skin' of steel reinforcement *inside* which the concrete is to be cast. For elements such as beams and columns where the leading section dimension might be upwards of 250 mm, the reinforcement would likely be provided as a fabricated rectangular casing, folded-up from steel coil in the 2-3 mm range of thickness. The hollow box would likely be held together by longitudinal MIG welds. In many applications there is scope and purpose served in positioning a similar but smaller steel box section inside the main one, and in the tension zone if the member is in flexure. This inner section most often would remain empty of concrete and could house services, fibre-optic cabling etc, while at the same time displacing ineffective tension concrete. It also contributes to flexural capacity in the event of fire. *Inherent* fire resistance can thereby be achieved. This resistance may need to be supplemented by extra fireproofing. The configurations have been experimented with and reported on [11].

When filled with concrete, so post- rather than pre-cast, such members exhibit considerable inherent ductility, strength and stiffness across *the whole range* of steel percentages. The tension reinforcement is also acting at maximum lever-arm. This is in contrast to bar reinforcement where there are definite limits above which the plastic characteristics are not achieved and cover reduces the lever arm. ERC can be pre- or post- stressed before filling: bar reinforcement cages cannot. There is considerable scope to assemble the elements into frame structures, with ease, simplicity of fabrication and handling. The jointing can use steelwork derived details, or new details and with a minimum need for temporary works. The casing is a permanent form for the concrete, thus eliminating one of the major sources of site waste. Because the concrete is shielded long term from ambient air, there is little or no carbonation of the concrete and hence the initial alkalinity of the concrete is retained. This ensures long term protection for the inner surface of the casing from corrosion and this despite the enclosed concreted remaining damp or even wet for long periods. These features also enhance the hardening, creep characteristics and strength development of the concrete.

Questions about the role of world cement production in the context of global warming arise and will require answers. Are there any feasible strategies for reducing CO_2 production per unit of cement produced while maintaining the essential properties of the resulting concrete? The world production of cement is of the order of 2Gtonnes. Lower levels of alkalinity might still provide adequate corrosion protection for some types of reinforcement – ERC for example. This is unlikely to be an option open for bar reinforced concrete. Reduced alkalinity probably requires a reduced content of calcium in the cement. All currently produced cements, including non-Portland cements such as High Alumina, have higher contents of calcium compounds than of silicates or aluminates. Significant changes to the chemistry will be costly to research and develop and may not result in suitable cements. But we need to explore the options. It should be expected that in a general sense, future construction practises will need to meet new, more stringent, sustainability targets.

Trabeated (framed) construction has been studied extensively from the plastic theory viewpoint [12]. Slabs have attracted less attention. One of the factors determining the directions for development of new technology is the availability of funding [13]. Compared to some other fields of study, construction does not compare well. Research programmes carry no guarantee of success but means must be found to advance the frontiers. We know that the infrastructure needs of society are accelerating at the same time that sustainability in all facets will require change to the technologies employed. Composite construction utilising a lightweight concrete floor supported on trusses was the type of construction adopted for the World Trade Centre. The dual-box ERC section shape briefly described above is an alternative. ERC is very straight forward to construct and provides multiple benefits. The steel of the inner box is better protected from fire than bar steel because the ‘cover’ is generally greater than for a conventional bar reinforced element. But above all a general aim in all construction should be to *simplify* processes and materials. ERC has much scope for achieving these and other beneficial outcomes. The dominant structural materials, steel and concrete, can and should be regarded as complementing each other rather than as rivals. Only then can each material contribute fully to a combined and enhanced composite material technology. Only then can all the inherent qualities of each of the materials be fully realised in a ductile, plastic behaviour [11].

5 OBSERVATIONS ON A THEORY OF DUCTILE SLAB BEHAVIOUR.

CTM’s 1966 paper [1] was a pioneering discussion of optimisation of the reinforcement layout for slabs in a plastic collapse state. Such studies have made considerable progress in the last forty years. A feature of most of the solutions that have been found is the dominant role played by geometry, most clearly seen in the shape of the deformed slab surface – the constant curvature properties. Further along this path the spanning directions emerge as part of the solution. It is these features which have hampered the full appreciation of the uses to which these studies could be put since they lead to extreme concentrations of reinforcement. But there are useful lessons to be learned: there is qualitative as well as quantitative knowledge to be gained.

The Upper Bounds on collapse loads are building blocks for yield-line theory in the Johansen tradition. These concepts have been widely studied. They have eventually gained acceptance, as have strip methods. But what can be said about Lower Bounds on collapse loads? Such studies have attracted only a tiny fraction of the total effort and attention accorded to Upper Bounds. Consider the following example:

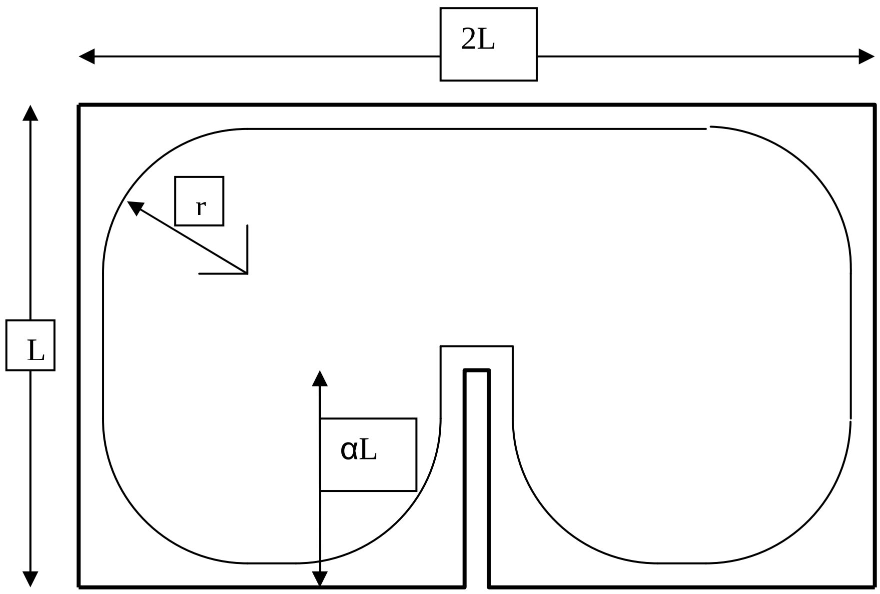

Fig. 1 Plan on Slab

Figure 1 is the plan view on a rectangular slab, edge supported on all sides and restrained against rotation along the edges, including the wall support which penetrates into the plan area. The approach we shall use to estimate the collapse load can cope with any shape of slab and any number of such wall supports. The only requirement is that each wall connects to the outer boundary at one end. The slab will be assumed to be ductile, isotropic, of uniform depth and uniformly loaded to collapse. Let the collapse pressure be p_c and the isotropic moment strength m/ unit length using a square yield criterion. Other yield criteria and non-isotropy can be incorporated. The aim is to estimate a Lower Bound value of the collapse pressure, p_L. The method of solution we adopt has been named the 'Comparison Method'. It is discussed in numerous papers and in the text [10]. A simple shape is chosen here to illustrate the approach. More complicated shapes can be dealt with by the same processes.

The two primary quantities needed in the calculation both relate to the shape of the slab. Here again is a situation where geometrical quantities play a paramount role. There is apparently much less formal application of statical concepts to achieve the results. The statics of the slab has been considered earlier and is contained in the equation (2). Two quantities are used to summarise the geometry. They are the *length of the perimeter* of the undeformed slab, denoted by B, and the *area* , A, of slab contained within the perimeter, B. In the present example B= (6+2α).L and A = $2L^2$. The width of the wall is here regarded as small. When the slab approaches the ultimate condition, a second internal boundary contour develops, consisting of hogging hinge-lines of rotation. This boundary, which we shall refer to as *b*, is a mostly a smooth curve that is tangential to the boundary B. At corners *b* will span round concave corners in circular arcs all of radius, r. At the end of the wall the hogging yield line forming part of *b* will follow the shape of the wall. For clarity Figure 1 shows the hogging yield-line inside rather than lying adjacent to the support boundary. We seek r_{min} as the value of the corner radius to minimise the ratio of *b/a*. Here *a* is the area of the slab within the boundary *b* that circumscribes the collapse mechanism.

It is straight forward to show that A=*a* +1.5.ω.r^2 and that B= *b* +3.ω.r. The parameter ω has the value (4-π). For a minimum of *b/a*

$$a.db/dr = b.da/dr,$$

$$\textit{or} \qquad (A - 1.5.\omega.r^2).(-3\,\omega) = (B- 3.r.\omega).(-3\omega.r).$$

This is a quadratic in r_{min} and simplifies to

$$1.5.\omega.r^2 - B.r + A = 0. \qquad (1)$$

Once the value of r_{min} is known for any particular value of the wall length, αL, the lower bound collapse pressure is given by [10]

$$p_L/m = 3.(1/r_{min})^2. \qquad (2)$$

Two lengths of wall are of particular interest, namely when there is no wall, that is the slab is a rectangle, Lx 2L, and also when the wall is sufficiently long for the slab to behave as two adjacent square slabs. In the first case, as the penetrating wall is shortened and removed then there are (quadrant) circular arc yield lines just in the four corners as compared with the six in the case of a finite length of wall. This requires that B = 6.L and coefficient of the quadratic term for r in (1) be reduced to unity. The solution is then r_{min}= 0.3510.L with the lower bound collapse load from (2) given by $p_L.L^2/m$ = 24.36.

The second case first arises when α =0.9431 and r_{min} = 0.2651.L. The collapse load is then $p_L.L^2/m$ = 42.69 and the slab is behaving as two adjacent square shapes. The collapse load remains unchanged as α approaches the value 1. The corner radius remains unchanged at 0.2651.L and two further corner radii appear to describe two square shapes. There is a monotonic decrease in the collapse load as the wall shortens. When α = 0.3211 the wall length is equal to r_{min} As the wall length reduces further the circular arcs of the hogging boundary yield-line at the wall subtend angles less than π/2 at their centres. Equation (1) then requires modification until the wall length is zero.

Unlike alternative methods the Comparison Method provides no information about the shape of the deflected surface produced by the collapse mechanism but nor is any of this information needed to proceed with a design. Other yield conditions, such as Tresca and von Mises, can be used so long as the appropriate circular plate solution is available. The value of the constant in (2) will change [11]. The calculated collapse loads for other yield criteria are likely to be very close to the exact solution but the nature of the bound may not be part of the solution [10]. These features are still being studied.

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