A Series of Articles on Steel Plates

Background

Ramsay Maunder Associates (RMA) is a small engineering consultancy set up as a vehicle for the research and development of robust software tools, based on equilibrium finite element technology, to assist the practising structural engineer, [1]. This work is self-funded through consultancy work, mainly for the nuclear industry in the UK. A particular research interest for RMA is the analysis of plates, both elastic and limit, and has resulted in an equilibrium finite element tool called EFE, [2]. This software is currently being incorporated into LimitState's SLAB software, [3], to provide complimentary lower-bound solutions (to SLAB's upper-bound solutions) for the assessment of reinforced concrete slabs. A workshop was held at the IStructE headquarters last year to demonstrate the new technologies to practising engineers and to obtain their feedback.

Introduction

It is, of course, essential that new software tools be fully verified against theoretical solutions, where these are known, or against other software tools. This has been possible for reinforced concrete (RC) slabs where a number of theoretical solutions are known to exist and where there is a long tradition of yield line solutions which has culminated in the extremely robust approach used in LimitState: SLAB. With this confidence RMA have been able to contribute to an IStructE Verulam debate on the effective width of RC slabs, [4], and to undertake collaborative consultancy work with an American Precast Concrete manufacturer, [5]. In collaboration with LimitState, RMA have also written an article explaining the modern limit analysis tools for the practising structural engineers and highlighting the need for caution when accepting unverified results, [6].

When it comes to steel plates, the collapse of which is governed by a different yield criterion than is applicable to reinforced concrete, then verification is less easily accomplished. There are a few known theoretical solutions available and to extend these to even common configurations, like a simply supported rectangular plate under a uniformly distributed load, one needs to make recourse to other numerical methods such as conventional finite element analysis. Conducting a limit analysis using conventional finite element techniques requires an incremental analysis adopting a non-linear (elastic/perfectly-plastic) material model and significant adherence to good simulation governance practices in order to produce reliable results. This has been achieved in collaboration with Engineering Software Research & Development (ESRD) Inc, [7], and their software StressCheck which was written specifically to provide practising engineers with a robust finite element tool capable of demonstrating sound simulation governance procedures. RMA act as Independent Technical Editors to NAFEMS (National Agency for Finite Element Methods and Standards), [8], and instigated and run their NAFEMS Benchmark Challenge over the last twelve months, [9]. The second of these challenges, [10], illustrates some of the issue practising engineers face when assessing a steel plate and demonstrates the need for further work in this area. The verification of EFE's plate limit analysis capabilities for steel plates would form the <u>first article</u> in the proposed series.

In comparing limit analysis solutions for a given plate configuration, but with the two yield criteria for reinforced concrete and for steel, it was realised that both the collapse mechanisms and collapse loads could be significantly different. This is of direct concern since the literature for the collapse assessment of steel plates, in both the UK and further afield, often suggests solutions based on the yield line approach and a yield criterion appropriate for reinforced concrete rather than steel. The second article aims to expose the difference in results obtained by the two yield criteria and to make recommendations for how these differences might be rationalised. These findings have been reviewed by Professor David Nethercot and his view was that RMA should approach the IStructE for possible publication.

Whilst limit analysis provides the collapse load, it is based on an idealised elastic/perfectly-plastic material idealisation and does not account for non-linear phenomena such as strain hardening and large displacements both of which are generally assumed to be strengthening phenomenon. The stiffening influence induced by membrane action can only be assessed when large displacements are considered and in addition to potentially influencing the collapse load is likely also to have an effect on displacements and therefore the serviceability limit state. The third article will look at these non-linear phenomena using conventional finite element analysis. It will also investigate the influence of corner uplift (uniaxial support systems) that may be of concern for plate configurations having two adjacent sides that are free or simply supported. The aim would be to provide sound guidance to the practising engineer on how these non-linear phenomena might influence his or her design or assessment decisions.

In exploring the published advice and results currently provided to practising engineers, a number of anomalies have been uncovered. Two particular publications have been looked at in this context and the results, whilst conservative, have been found to be ripe for updating using modern software tools, [10]. The texts are Roark's "Formulas for Stress and Strain" and the SCI's publication "Steel Designers' Manual" (SDM), and the plate configurations of interest are the common ones of a rectangular plate loaded with a uniformly distributed load and either simply supported or fixed around all sides. In the light of RMA's findings, the publishers of the Roark text (McGraw-Hill) have request that we develop a new section for the next edition of their publication to include an update of their results with those developed from EFE. The SDM, whilst stating that the loads they report are 'ultimate load capacities', is actually showing the loads to first yield based on an out-dated and rather inaccurate elastic approximation. RMA have discussed the possibility of providing an update to the SDM results with Graham Couchman of the SCI. Unfortunately, however, due to financial constraints, and a perceived lack of interest from their members, they are not able to get involved with this work. It is interesting in this context to note that the AISC does now provide both 'ASD' and 'LRFD' load values. The fourth article will offer an explanation as to why both the elastic and limit loads in the published texts are inaccurate and will present practising engineers with an updated set of reliable results for the simply supported configuration. The fifth article will perform the same function as the previous article but for the fixed plate configuration.

Article 1: A Lower-Bound Limit Analysis for Steel Plates

This follows on from the Jackson/Middleton article published in the IStructE Magazine (vol. 91, issue 1, 2013, 34-40) on RC slabs but uses the von Mises yield criterion which is appropriate for steel plates. Verification for such a code is not straightforward but has been done using conventional incremental FEA and a non-linear material (elastic/perfectly plastic) model. With this verification, together with the assuredness that the method is always safe, one can confidently consider limit analysis in the design and/or assessment of practical problems as allowed in the limit state design philosophy in, amongst others, EC3.

Authors: Ramsay, Watkins & Maunder

Article 2: Is Conventional Yield Line Analysis Appropriate for Steel Plates?

Yield line analysis, an upper-bound technique, has long been used, generally as a manual technique, for the limit analysis of reinforced concrete. It has also found wide use in steelwork, e.g., the design of end plates in the connections of beam/columns, as presented in, amongst others, the Green Book. However, since the yield line technique generally uses a square yield criterion, the resulting collapse loads can be significantly inaccurate for steel, which more closely obeys another yield criterion, i.e., the elliptical von Mises criterion.

Practical examples will be presented where the collapse load predicted by the yield line technique, with the square yield criterion, is between 42% too conservative and 16% on the unsafe side of that achieved using the more realistic von Mises criterion. This claim has been confirmed via a high-quality reference solution based on the lower-bound technique of Article 1.

The ideas to be presented here have been discussed with Professor David Nethercot who suggested we approach the IStructE with a view to publishing these findings.

Authors: Ramsay & Maunder

Article 3: How Limit Analysis of Plates compares with full Non-Linear Analysis?

It is recognised that limit analysis does not account for certain non-linear phenomenon e.g. strain hardening, and large displacements. These are generally considered as strengthening phenomena so that a limit analysis solution is always deemed to be conservative. Nevertheless, when thin plates are being designed, serviceability limits may also require non-linear behaviour to be investigated. Another non-linear concern is that of corner uplift (uniaxial supports for simply supported configurations) and how it influences the outcome of a linear elastic analysis. These questions will be investigated using non-linear finite element analysis with a view to presenting some guidelines to the practising engineer.

Authors: Ramsay, Reijmers & Maunder

Article 4: A Review of some Published Ultimate Load Capacities for Steel Plates (Part I)

The practising engineer may reference a number of texts to establish the ultimate load capacity for a standard simply supported rectangular plate. However, he/she will find that various publications provide different results, and these differences can be very significant. For example, the values given for a (particular plate) in Roark's "Formulas for Stress and Strain" and the SCI's "Steel Designers' Manual" are 176kPa and 103kPa. The verified lower-bound approach, which gives a value of 231kPa, shows that, whilst conservative, neither are correct. Overt conservatism can lead to unnecessary remedial work when assessing a plate for a new duty or wasted extra material in a design scenario and so it is important that these results be corrected.

This article will briefly explain the reasons why these differences have occurred and provide a solution to this problem in the form of Design Charts for the practising engineer.

Authors: Ramsay, Al-Gahtani & Maunder

Article 5: A Review of some Published Ultimate Load Capacities for Steel Plates (Part II)

Part II of this article will consider the ultimate load capacity for a standard fixed rectangular plate, for which similar issues (to those for the simply supported case) exist in published results. This paper will briefly explain the reasons why these differences have occurred and provide a solution to this problem in the form of Design Charts for the practising engineer.

Parts I and II of this article consider idealised support conditions, but in reality, it is emphasised, that the real situation will lie somewhere between these two idealised support conditions.

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References

1. http://www.ramsay-maunder.co.uk/
2. http://www.ramsay-maunder.co.uk/downloads/Equilibrium_models_for_lower_bound_limit_analysis.pdf
3. http://www.limitstate.com/slab
4. http://www.ramsay-maunder.co.uk/downloads/verulam_complete.pdf
5. http://www.ramsay-maunder.co.uk/downloads/precast_roof_slabs.pdf
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