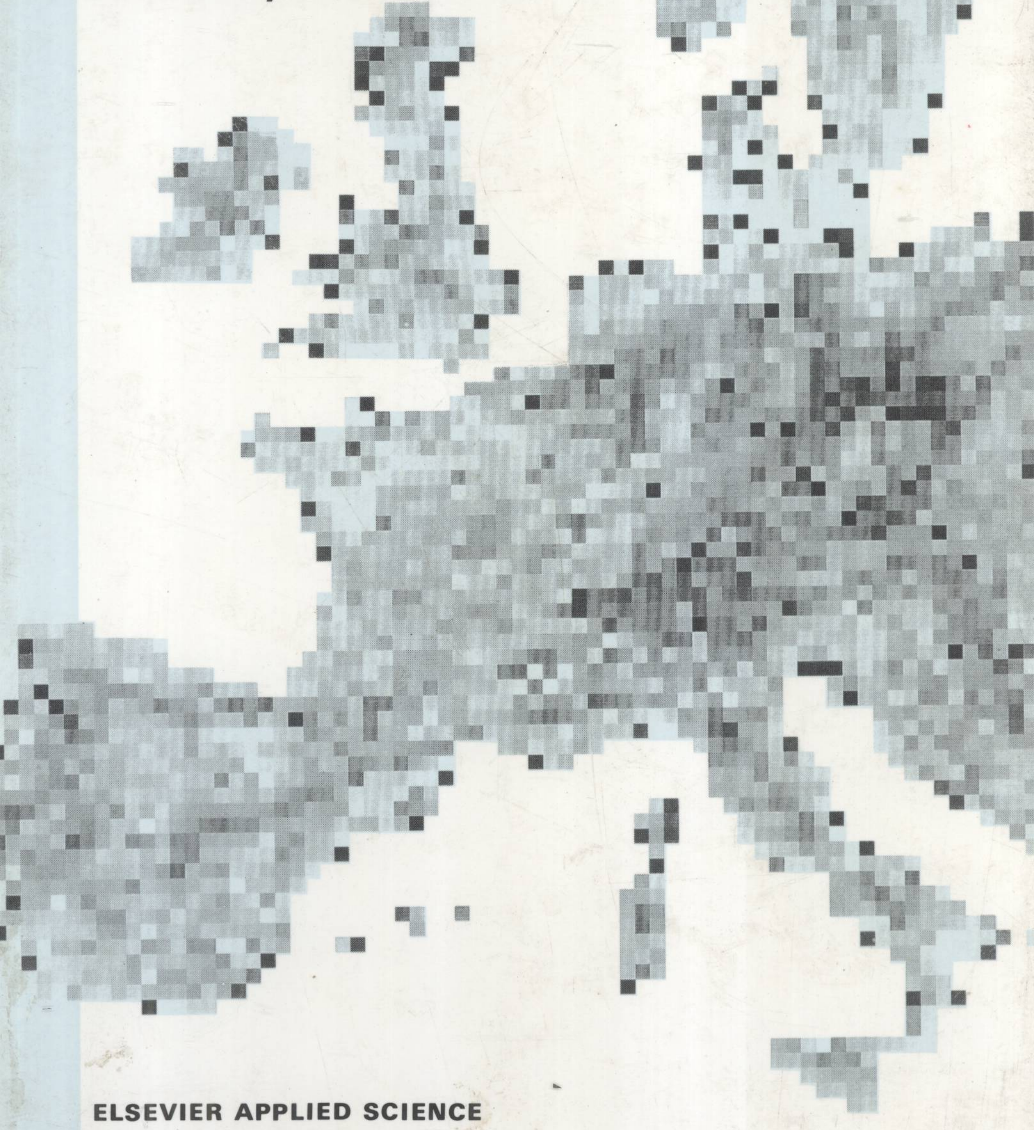
ALUMINIUM STRUCTURAL ANALYSIS

Recent European Advances

Edited by P. S. Bulson



ELSEVIER APPLIED SCIENCE

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Recent European Advances

A collection of papers on aspects of research and design in structural aluminium with particular reference to the needs of a future European code of practice.

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Preface

This book looks ahead to the design of aluminium structures in the remaining years of this century and the early years of the next. It will be a time of change in the world of structural codes of practice and specifications for general engineering, with the introduction of Eurocodes and the need to harmonise these with national and international practice. Design methods are changing too, with most engineers now aware of limit state methods and their advantages.

There has been much interaction recently between the leading authorities in structural aluminium in Europe and North America, in anticipation of the transition to new codes of practice. In the UK the British Standards Institution is about to publish a new code on Structural Aluminium. In other countries of the European Community much effort is being put into the drafting of the aluminium sections of the European Convention for Constructional Steelwork codes. The Italian Standards organisation has produced a new Aluminium code of practice. The German government is examining a replacement for their longstanding code. There has been a recent resurgence of effort under the aegis of the International Standards Organisation towards an international code for Structural Aluminium and this, of course, has included the USA and Canada. Much needs to be done to effect a dovetailing of these diverse interests, all of which see the need for a progressive attitude to design.

The purpose of this book is to help towards an international view of the subject, with particular reference to the problem of bringing the

European authorities into a closely-knit mode. It has been decided, therefore, to bring together the writings of six acknowledged experts in the field from four European countries, each contributing to an aspect of the subject by drawing from long experience of structural aluminium in design, testing and analytical research. All the experts have made, or are making, major contributions to code-writing. This choice of authors is particularly important because the time is not too far distant when work on a new Eurocode on Aluminium Structural Design will be in full swing.

The book opens with a chapter by the editor and Dr Cullimore which is designed to set the scene by reviewing the development of aluminium in structural engineering, and which highlights design principles and problems. The design principles are aimed particularly at limit state design and design for reliability and economy. The problems include the influence on design of the low elastic modulus and its effect on stability, vibrations, fatigue and fracture mechanics; also the low melting point and the change in properties in heat-affected material. The chapter concludes with thoughts for the future.

The long second chapter is a major joint contribution by two well-known academics from the mainland of Europe. Professor F. Mazzolani from the Universita di Napoli and Professor G. Valtinat from the Technische University Hamburg-Harburg, FRG combine to discuss the behaviour of bars, beams, columns and beam-columns. There has been much fundamental research on this subject at their respective universities in support of the European Recommendations for Aluminium Alloy Structures (ERAAS), and Professor Mazzolani has published a text book on aluminium structures. Both professors are also members of the International Standards Organisation committees preparing an international standard for structural aluminium.

Although the second chapter includes reference to the torsional and lateral stability of members, it was thought appropriate that the work in these areas in the UK should be reviewed separately. Chapter three, therefore, is written by Professor Nethercot of the University of Nottingham, and summarises the considerable range of testing and analysis dealing with the torsional and lateral buckling of struts and beams, undertaken by specialists in British universities and elsewhere in the past 40 years. Professor Nethercot has contributed towards the preparation of the new UK code of practice, and is also concerned with the British input to the new International standard. Because he is also very well known in Europe for his work on steel structures, he is able to draw comparisons in the way the two materials are treated in design codes.

Professor H. R. Evans, head of the new School of Engineering at the University of Wales at Cardiff, is the leading expert on the design and analysis of aluminium plate girders. Research on plate girders has been associated with Cardiff for a long time, and the structural testing facilities there are of a high standard. Chapter four, therefore, gives Professor Evans an opportunity to summarise recent work at Cardiff on the ultimate strength of aluminium plate girders, and to show how this work has been developed for the new UK code of practice. It is hoped that this approach could form the basis of design clauses in a future aluminium Eurocode. The work at Cardiff has been aimed particularly at the effect on plate girder strength of welding, especially in higher strength alloys in the 6*** and 7*** series.

Problems of welded construction are also the subject of the following chapter, by Dr Soetens of TNO Building and Construction Research at Delft in the Netherlands. The stress analysis of welded joints and the influence of the heat affected zone is a particularly important subject, and Dr Soetens has become a leading authority in the field through his work at Delft. In recent publications he has examined the effect of deformation capacity on the behaviour of welded joints, and has used finite element analysis to simulate the behaviour to failure of typical welded test-specimens. Here he presents a state-of-the-art review of the analysis of fillet and butt-welded joints.

Dr Cullimore, formerly of Bristol University, writes on bolted and rivetted joints for general engineering structures in aluminium. He also summarises his own research into the strength of friction-grip bolted joints. His research on the analysis of the latter has been confirmed by extensive test programmes at Bristol, and his chapter is therefore a timely summary of recent progress. His work has been partially sponsored by the UK Ministry of Defence, whose military engineers have particular structural problems for which friction-grip bolted joints are the best answer.

We have brought together, therefore, a selection of experts from many of the major research areas in structural aluminium. Readers are reminded that the subject matter of the book is aimed at the design of aluminium buildings, bridges, ships, vehicles, towers and similar structures, but not at the design of aircraft, pressure vessels or space vehicles. There still exists a clear division between the general world of aluminium structures and the specialist world, such as aircraft structures, where safety, reliability and economy are bought at great expense. It will be interesting to see if these areas grow closer together as time goes by.

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ABSTRACT

After a short review of the growth of structural aluminium as a general engineering material, attention is focussed on some of the major design principles and problems faced by designers who use structural aluminium. Safety and serviceability are key elements of limit state design, and the use of partial factors of safety in recent codes of practice is discussed. A problem of particular interest to designers of welded aluminium structures is the presence of heat-affected zones and how these are allowed for in rules. The way that the new Code of Practice, BS 8118, deals with the contribution of heat-affected material to the strength of members is summarised.

The analysis of tension and compression members is discussed, and this is followed by a description of the difficulties associated with structural fatigue. Methods of dealing with this problem include the use of fracture mechanics for particular relationships between stress range and life. Design problems of welded joints are briefly mentioned, and the chapter concludes with a review of the problems of structural testing and quality assurance.

1 INTRODUCTION

Aluminium is an attractive material, light, strong and clean. It is not surprising that when first produced chemically it was classed as a precious metal, and it was only after the discovery of cheap methods of production from bauxite using electrolytic processes that its use in engineering structures became a possibility. Luckily the properties of the alloys of aluminium fitted the requirements of aircraft designers, so there was much money available for research and development from the 1920s onwards. The development of new alloys and of new methods of production was linked to the expansion of the military and civil aircraft industries and to the advent of the all-metal aircraft body. The need for new materials in the aeronautical and aerospace fields led the way for research in the past, and it still does today.

In the early days aircraft wing structures often used extruded aluminium alloy booms, or booms formed from shear webs and reinforced wing cover. Fuselages used thin sheeting reinforced with light stringers. Increases in ultimate tensile strengths were brought about by varying the alloying elements, using copper, zinc and magnesium. Methods of jointing were developed to augment riveting. Spot welding was used, though not in primary structures, and the main progress was in the use of rapidly applied blind fasteners and bonding.

Aircraft designers soon realised that to increase the strength of aluminium alloys without a corresponding increase in the relatively low modulus of elasticity could lead to problems in the fields of buckling, fatigue, vibration, deflection and aero-elasticity. Consequently these subjects were in the forefront of structural research between and after the two world wars. It was soon recognised that the 'allowable stress' notion of design was very unsatisfactory. What was adequate for the designers of steel and wrought iron structures in the nineteenth century was far from suitable for engineers in the aeronautical world who were trying to accommodate safety, speed, economy and efficiency into their structures in a very hostile environment. The importance of ductility and the crack-free redistribution of high stresses around rivets, for example, indicated that an ultimate and serviceability limit state philosophy would be needed if progress was to be made. Matching the ultimate resistance of components to factored loads and matching the behaviour of components to acceptable levels of deformation and vibration were the true measure of the designers' craft. These ideas were crystallised by the 1950s into the statistically based philosophy of structural safety.

As experience with the design of aluminium structures grew it was natural for the producers of the metal to look for new markets. An obvious field was the construction industry—the design and manufacture of buildings, frameworks, bridges, and smaller components such as windows, doors and canopies. Other structural areas where aluminium could be used effectively were in shipbuilding, road and rail transport, pressure vessels, and in military engineering. The quality of structural design and testing in many of these areas was relatively backward when compared with aircraft, and still is, so it became necessary to make progress carefully. Allowable stress design was adopted, but backed up by extensive research in the universities and elsewhere into problems of instability and deformation in typical construction industry components. The lateral buckling of beams was investigated, as was the compressive buckling of struts and plates, the torsional behaviour of open sections, the response to loading of flexible space frames with secondary stresses, and the behaviour of plate girders with thin webs and transverse stiffeners. Fabrication, erection and protection were also important in structures that might not be subjected to the high level of quality assurance associated with the aircraft industry.

In challenging the use of steel for general engineering structures aluminium suffered two drawbacks, the price of the material and the cost of structural assembly. Kilogram for kilogram aluminium was still relatively expensive, so the case for its use had to be carefully examined. Structures where a large reduction in dead-weight was needed, particularly in the superstructure of road and rail vehicles, military structures, and long span frameworks and bridges, were good candidates for aluminium. The costs of fabrication and assembly were influenced by the lack of information and experience in the welding of the metal, and it was therefore in this area that much research and development was carried out in the 1950s and 1960s. The successful welding of aluminium is now an accepted feature, and modern codes of practice pay much attention to it. The heat from the welding process produces a reduction in strength properties close to welds in heat-treated alloys, and the local stress-raisers in certain types of welded detail have a damaging effect on fatigue life. The way that the heat-affected zone is dealt with in the stress analysis of designs now forms an important part of design codes of practice.

The world of general engineering structures is now acknowledging the importance of limit state design, and abandoning, not without some protests, the old ways of permissible stress. This acknowledgement is not surprising. As our methods of stress analysis become more sophisticated, higher and higher local stresses are discovered in the structure, and to apply the permissible stress philosophy in these circumstances can lead to very uneconomic results. Of course, the need for economy applies to steel and concrete as well as aluminium, and the new Eurocodes in all these materials are therefore written with a limit state design philosophy.

There are many examples of the successful use of aluminium in the constructional field. A survey was carried out in 1983 of six aluminium highway bridges in the USA and one in Canada, erected in the years between 1948 and 1963. Riveting and welding were used in their construction. It was found that no painting or major maintenance had been required for the aluminium superstructures, there was no fatigue cracking in the riveted bridges and only minor cracking in the one welded structure. The lives of all the bridges were expected to be at least 50 years.

In Britain a major military bridge system, the Medium Girder Bridge (MGB), has been in continuous service for 20 years. It is an all welded, heavy duty structure, which is assembled rapidly from component parts that can be man-handled. It is manufactured from a type of 7020 alloy. Time and money were spent to develop a version of the alloy that was very resistant to stress corrosion, but the fact that bridges were deployed world-wide in a range of temperatures and conditions, with minimal structural problems, shows that the cost of the research was justified. In the military field aluminium is also used for prefabricated trackways, support boats, bridge inspection platforms, and for the structures of combat vehicles.

In addition to the more conventional structures such as masts, towers, railway carriages and road vehicle superstructures, aluminium has been used for mosque domes in Africa and the Far East. These have been constructed in the form of double-layer space frames to give architecturally interesting buildings. No doubt in the future there will be many other architectural concepts that require the use of tubular aluminium to give space and strength. There has also been an interest in the use of aluminium for the topside structures of offshore oil rigs. Additional protective structures, if required, must be added without seriously overloading the existing structure, and aluminium is an obvious candidate material.

At the time of writing much research effort is being devoted to second generation aluminium lithium alloys, the use of which can reduce airframe structural weight by 7–15% depending on the application. Advanced alloys are being developed from wrought powder metallurgy technology, which results in a rapid solidification process. This produces alloys resistant to stress corrosion cracking and exfoliation. Aramid aluminium laminates are also under development, to combine high strength sheet with the fatigue resistance of aramid fibres. The aerospace industry is a major user of high quality aluminium premium castings, particularly in the primary structure of unmanned missiles. The use of these new alloys and processes will no doubt spread to general engineering structures in time.

2 SAFETY AND SERVICEABILITY

In all modern codes of practice structural safety is established by the application of the partial safety coefficients to the loads (or 'actions') and to the strength (or 'resistance') of components of the structure. The new Eurocodes for the design and execution of buildings and civil engineering structures use a limit state design philosophy defined in Eurocode No. 1 (common unified rules for different types of construction and material).

The partial safety coefficients for actions (γ_f) depend on an accepted degree of reliability, which is recognised as a national responsibility within the European Community. The probability of severe loading actions occurring simultaneously can be found analytically, if enough statistical information exists, and this is taken into account by the introduction of a second coefficient, ψ. The design value of the action effects (when the effects are unfavourable) is then found by taking values from γ_f dependent on the type of loading and values for ψ that take account of the chances of simultaneous loading. Experts suggest a value of γ_f of 1·35 for permanent loads, such as the dead load of bridge girders, and 1·5 for variable loads such as traffic loads or wind loading. These values are similar to those proposed in the 1978 edition of the European Recommendations for Aluminium Alloy Structures produced by Committee T2 of the European Convention for Constructional Steelwork (ECCS–CECM–EKS). The loading actions on members are found by an elastic analysis of the structure, using the full cross-sectional properties of the members.

The partial safety coefficient for actions takes account of the possibility of unforeseen deviations of the actions from their representative values, of uncertainty in the calculation model for describing physical phenomena, and uncertainty in the stochastic model for deriving characteristic codes.

The partial safety coefficient for material properties (γ_m) reflects a common understanding of the characteristic values of material properties, the provision of recognised standards of workmanship and control, and resistance formulae based on minimal accepted values. The value given to γ_m accounts for the possibility of unfavourable deviations of material properties from their characteristic values, uncertainties in the relation between material properties in the structure and in test specimens, and uncertainties associated with the mechanical model for the assessment of the resistance capacity. Typical values in recent European codes of practice for aluminium are $\gamma_m = 1{\cdot}2$ and $1{\cdot}3$, on the assumption that properties of materials are represented by their characteristic values.

A further coefficient, γ_n, is often specified in codes, and this can be introduced to take account of the consequences of failure in the equation linking factored actions with factored resistance. It is often incorporated in γ_m. It recognises that there is a choice of reliability for classes of structures and events that takes account of the risk to human life, the economic loss in the event of failure, and the cost and effort required to reduce the risk.

The ultimate limit states defined by the use of the above factors refer to failure of members or connections by rupture or excessive deformation, transformation of the structure into a mechanism, failure under repeated loading (fatigue) and the loss of equilibrium of the structure as a rigid body.

Serviceability limit states, according to most definitions, correspond to a loss of utility beyond which service conditions are no longer met. They may correspond to unacceptable deformations or deflections, unacceptable vibrations, the loss of the ability to support load-retaining structures, and unacceptable cracking or corrosion. Because certain aluminium alloys in the non-heat-treated condition, or in the work-hardened condition, do not have a sharply defined 'knee' to the stress/strain curve, it is sometimes possible for unacceptable permanent deformation to occur under nominal or working loads. The same may be true for alloys that have a substantial amount of welding during fabrication.