THEORY & PRACTICE OF MODULAR COORDINATION

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ABSTRACT

In this paper Professor Brookes will review the programme of introduction of dimensional coordination and modular coordination in UK starting from the Hertfordshire Schools of 1955. He will describe the various attempts by government and other bodies to force the mandatory use of dimensional coordination and his own involvement with the PSA Method of Building programme in 1970's and the building of a full size test mock-up using five different types of structural frames at Building Research Establishment, Garston.

He will describe his own PhD thesis on tolerances and jointing and mainly the general conclusion that 5% of building costs arise from remedial work caused by inaccuracy of construction lying outside the tolerances allowed for in design.

He concludes that in recent years the situation has not necessarily improved. As a cladding consultant he is often called to advise on jointing failure arising from gaskets and sealants being outside their permissible joint sizes due to inaccuracy in the structural framework.

In his own work at Singapore Arts Centre and Federation Square Melbourne, he was well aware that allowance for 3-dimensional tolerances must be provided at all critical interfaces and that all members of the building team including subcontractors must be aware of and agree the tolerances in construction related to critical dimensions and grid lines before starting manufacture and assembly.

KEY WORDS

Modular, Claddings, Tolerance

INTRODUCTION OF MODULAR COORDINATION IN THE UK

Following the second world war various types of prefabricated houses were developed in UK and in the schools building programme Hertfordshire County Council (1955) led the way in establishing a flexible means of construction based on modular assembly (Russell 1981).

A key part of the Hertfordshire philosophy was the use of a planning grid enabling the plan to change size and shape at any point of the grid. In an article signed "the County Architects Dept" in the Architect and Building News in 1948 (Hertfordshire Architectural Department 1948) the advantages to the grid are simply set out after making an analogy between the movement of a chess piece and the movement of components on the planning grid.

At the same time in USA Charles and Ray Eames were designing their own house in Santa Monica using standard windows and doors straight from the manufacturers catalogue mounted on to a cross braced steel frame(Mac Callum 1959). This house became the icon for system building and went on to influence the UK designers of the consortia building programmes such as SCOLA and CLASP.

Figure 1: Eames House. Santa Monica. USA.

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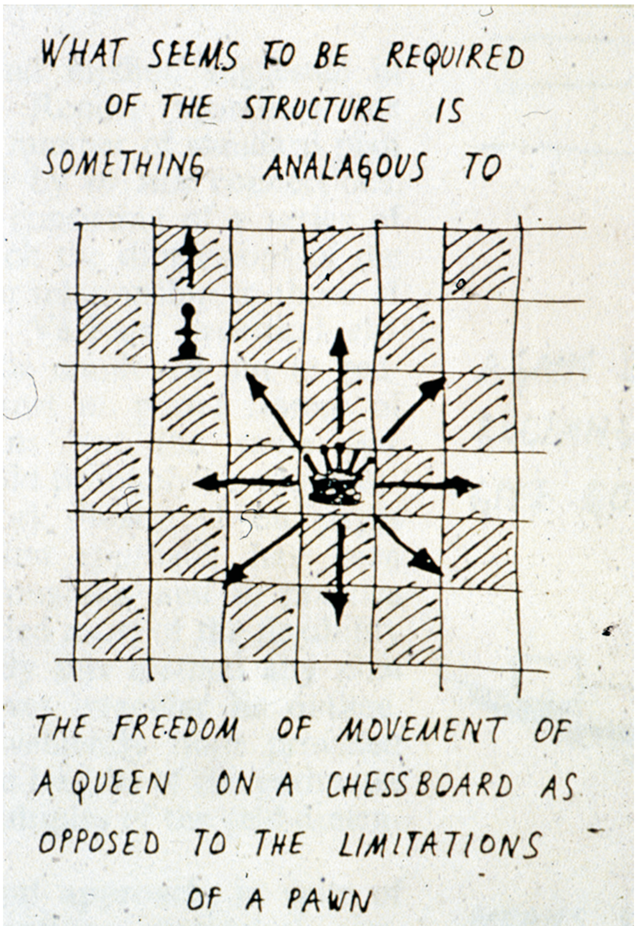

Figure 2: Movement of a chess piece demonstrating adaptability

The Eames house and others engendered enormous enthusiasm amongst architects that an industrialised vernacular was not only possible, but at hand. In UK the Modular Society was founded in 1953 by Mark Hartland Thomas which sought to bring about the idea of a dimensionally related building industry vernacular through a series of ground rules the most crucial one being the use of the basic module of 4 inches or 100 mm for all component sizing. This was not particularly a new idea. Albert Farwell Bemis had proposed a similar three dimension dimensional module based upon the 4-inch dimension in USA in 1936 (Bemis 1936).

Many of the protagonists of the modular idea, including the Prime Minister Harold McMillan saw it as a way of drawing Britain and the rest of Europe closer together. Driven by the zeal of Thomas and others the Modular Society became exceedingly influential in making the case for modular coordination through articles and publications including the Modular Quarterly and the Modular Primer. The latter written by Corker and Diprose and published in the Architects Journal for 1 Aug 1962 became the handbook for a whole generation of architects intent on bringing some rationalisation into the British building industry(Corker and Diprose 1963).

1961 also saw the publication in English of Konrad Wachsmann's. The Turning Point of Building which contains one of the clearest statements of the case for mass production and industrialised buildings using the ideas of modules and standardisation (Wachsmann 1961).

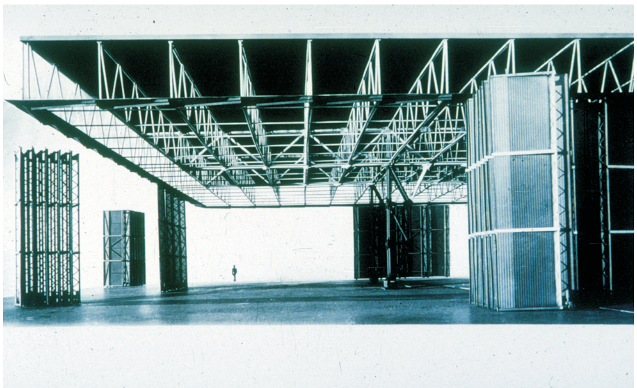

Figure.3: Adaptability of components (Konrad Wachsmann)

The process of metrication began in Britain in 1965 in the building industry. The programme allowed ten years to 1975 for the changeover and made necessary the rewriting of Britain standards and related documents. This gave an opportunity for modular ideas to be incorporated and to become mandatory. Several Government Departments were involved in introducing in their own large building programmes the principles of Dimensional Coordination (Martin 1965).

A determined effort to establish the viability of the performance standard approach for component procurement linked to an open system of components using dimensional co-ordination was made by a group set up in 1968 at the Ministry of Public Buildings and Works London led by Colin Pain and known as Method of Building Group.

Pain went to visit Ralph Iredale in USA in 1968. Iredale had previously worked for CLASP and NENK systems and then emigrated to California to work with Ezra Ehrenkrantz on the Californian Schools Programme SCSD.

In turn Ehrenkrantz had studied with Wachsmann and thus the link towards component building using ideas of modular construction, space frames, lightweight steel framing etc were formed. Later Norman Foster and Richard Rogers went on to study at Yale in the Master Programme of the same School of ideas.

I joined Method of Building Group in 1970 to prepare documentation on design discipline and design requirements that by 1971 had become mandatory for the MOPBW building programme. A similar approach was also adopted by the

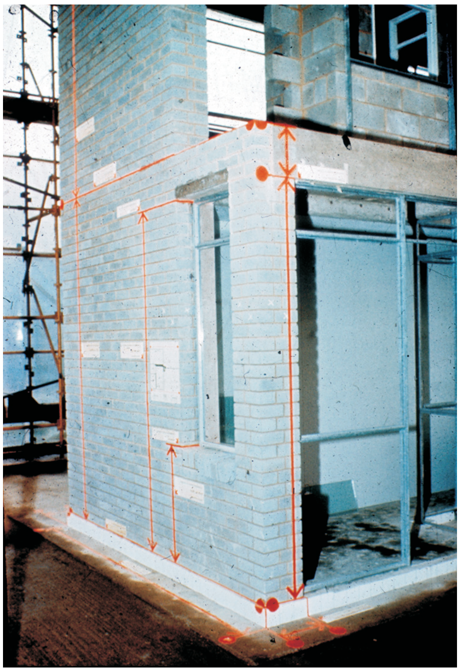

Figure 4: Dimensional control lines on the Method of Building Rig showing components within their own 'basic' space.

Department of Education & Science and the Ministry of Health.

During this time although the advantages of procurement using performance specifications were becoming clear there was a nagging doubt about the limitations of conventions for fixing and jointing within the dimensional framework particularly as the strict rules of dimensional co-ordination concerned the question of components "keeping station within their modular (basic) space". A full size mock-up was tested at the Building Research Station in Garston UK to check principles of jointing using five different types of structural frameworks.

In 1967, J.F. Eden put the problem more directly to the dimensional co-ordinators when he cited the development of the engineering industry whose success in mass production architects were trying to emulate (Eden 1967). He pointed out that the accuracy and interchangeability of parts in engineering relied upon the definition early in its development of sets of standard for joints.

Thus the way in which the parts fitted together is very much more crucial that the parts to be themselves dimensional co-ordinated. Later his advice was taken by Bruce Martin in his book 'Joints in Building' (Martin 1977) but at the heyday of dimensions co-ordination in 1968 such advice was hard to swallow.

The main obstacle was that many weatherproof joints need overlap or rebates thus the rule that "every component should not exceed its own basic space" could not always apply.

Further the effect of tolerance if allowed within the basic space can lead to uncomfortably wide joints at the edges of the component.

Early studies of modular theory had made some attempts to point out the implications of manufacturing erection and movement tolerances in component sizing but had not put any serious values of this allowance. Studies by Pietro N. Maggi in Italy had identified problems of tolerances in building as early as 1961 (Maggi 1961). This led to a proposal to use statistics as a method of combining likely errors in an article in Modular Quarterly by Sefton Jenkins and Mak in 1963. However this proposal came too late for the statistical concept to be included in the British Standard (BS 3626:1963). "Recommendations for a System of Tolerances and Fits for Building".

Unfortunately early thinking was pre occupied by a misunderstanding of terms. This is illustrated by a paper on definitions included within Modular Quarterly Summer 1958 in which "deviations" are confirmed as 'the allowance to take account of tolerances' rather than the other way around. Secondly there occurred not only in the Modular society but by others in the field an over simplification that each component must keep station within the co-ordinating lines. Even though the working committee of the Modular Society showed in its report Winter 1959 the column face deviating over the modular plate this diagram was declared incorrect at the main discussion meeting in March 1960. The extent of the joint size variation resulting from this over simplification was either not appreciated or ignored.

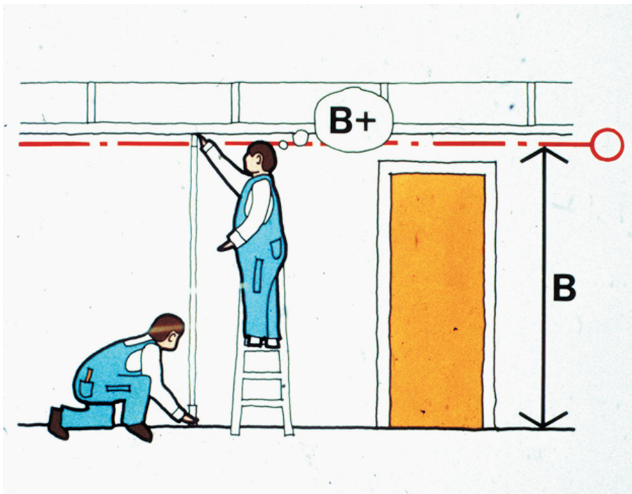

Figure.5: Tolerances in Construction meant that components sometimes lay outside their own 'basic' space.

BUILDING RESEARCH ESTABLISHMENT

Following widespread dissatisfaction with BS 3626 work was started at the Building Research

Establishment mainly by Harry Harrison and Ron Bonshor to determine more sensible methods of work sizing and determination of tolerances. This led finally to the production of a new British Standard DD 22 in 1972. "Recommendation for the co-ordination of dimensions in building tolerances and fits for building".

Even so there were still limitations to the methods as proposed.

The first was that permissible deviations for various methods of construction were not available for insertion in the formulae suggested by DD22. The British Standards had published in 1969 the provisional document on accuracy in building (PD 6440) (14), which has a section giving permissible deviations for erected building elements. In order to check the validity of these values an accuracy surveys programme was initiated by BSI in December 1972. The programme was devised by BSI with the assistance of BRE and called for the checking of about 50 000 individual items of some 320 building projects of various types.

Building contractors were asked to execute the actual measuring and to feed back data forms containing the required measurements of the erected items. Sixteen different data forms were devised to cover the different types of items (distance between walls, levels of floor, straightness of walls etc.). This survey eventually provided a realistic Code of Practice of standards of accuracy that can reasonable be achieved for different forms of structure. The designer was then able to include the deviations from this new Code into the DD 22 formulae.

The second main difficulty with the application of DD 22 was that the methods tends to produce a single size peculiar to each application of a component. For this reason BRE (Sefton Jenkins and Mak 1963) had produced graphical aids for Manufacturers and Designers whereby a range of sizes, rather than a single size, are given depending upon the conditions of use of the component (Bonshor 1972). These graphical aids are based on an idea by John Ritter to use computers for finding the optimum sizes of components using the DD 22 formula. The important merit of these aids is that they enable choices—and their consequences—to be seen rather to dictate particular action.

As such, they offered guidance on suitability for particular uses and suggested the steps to be taken to achieve satisfactory use.

PHD THESIS AT LIVERPOOL UNIVERSITY

Thus by the time I started my PhD thesis at Liverpool University in 1973 the stage was set. My main tasks were to study:

1) To what extent is remedial work necessary as a result of variability in construction lying outside tolerances in design?
2) Where do the major difficulties lie?—An investigation of issues arising from the case studies
3) What are the costs of these difficulties?
4) Why doesn't the Building Industry avoid these problems through the use of design aids and Standards?—A review of existing Standards and designers attitudes.

The research (Brookes 1976) encompassed the study of thirteen building projects then under construction using precast concrete panels with insitu concrete frames. Measurements were taken of the variability achieved on site and the factory and the resultant range of joint sizes between components. In all cases the variability (accuracy of assembly) exceeded the tolerances specified. Joint sizes were always larger or smaller than designed.

The case studies pointed to three main conclusions:

1) As the numbers of interrelated critical dimensions increases the chance of misfit increases and thus the critical points in assembly should be kept to a minimum.
2) Three dimensional tolerance requirements have the effect of increasing the number of critical dimensions.
3) Misunderstandings between designers, manufacturers and constructors occur when the permissible deviations on critical dimensions are not given or made clear from the drawings or in specification. The use of assembly drawings showing cladding components related to the structural framework with all ancillary fixing and jointing methods and with their tolerances clearly stated would reduce this misunderstanding. It was estimated that the cost of remedial and rectification work resulting from accuracy of assembly lying outside the tolerances of the design was 5% of the cost of building for the critical activities in the building process such as cladding.

At that time there were many ideas for further study of this problem. For example CIB W49 subgroup W6Z 'Economical Tolerance' was formed to analysis faults arising from inaccuracy and several congresses were held to study tolerances and dimensional control. Standards were produced and many learned papers were presented on this subject. As my career progressed first as an Architect and later as a Cladding Consultant it became clear that over and over again both the design team and the contractor did not communicate to each other the three-dimensional tolerances of critical moments of the assembly.

I will now review two projects where I have recently been involved where the need to allow tolerance in the fixings was critical to the performance of the assembly. The first is Singapore Arts Centre (D.P. Architects) the second is Federation Square Melbourne (architect Bates & Smart).

THE SINGAPORE ARTS CENTRE

The Singapore Arts Centre roof was originally designed as a monolithic shell by Michael Wilford. I worked with Atelier One London to develop a dynamic form of triangular glass panels with aluminium sunshades. Here we were consultants to the client assisting the German subcontractor Mero to devise a system capable of meeting the client's requirements not only for appearance of the performance requirements for weathering and wind loading. The concept originally developed by the engineerings office Atelier One was a sculpted non-linear form of the concert hall and lyric theatres with an articulated surface using a space frame grid with glazed infill and aluminium shading devices. The modelling of surface geometry using Micro station creates a mesh of equal-length elements to standardize their manufacture.

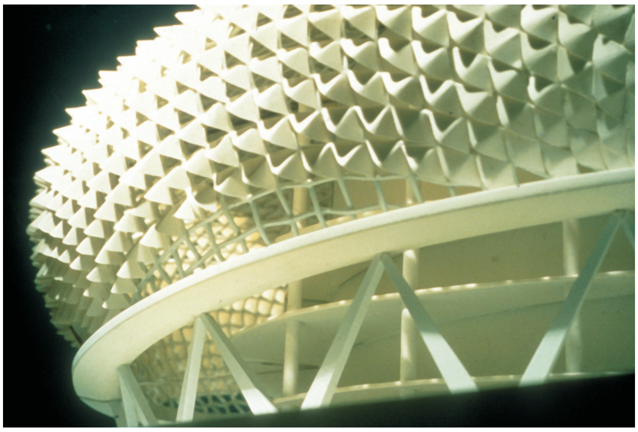

Figure 6: Early model of Singapore Arts Centre.

Working closely with the architect MWP/DPA a generic solution of a double layered jointing system at the edges of the triangulated glass panels with their moveable sunshades.
The main problem was the large potential number of variants in the aluminium sunshades and the need to respond to the complex geometry whist at the same time providing assurance that the building would not leak particularly if the Prime Minister was sitting the audience at the time of a heavy Singapore rain pour.

The system eventually developed and constructed by Mero Germany consists of a series of nodes and chords with an ingenious net of e.p.d.m. drained gaskets to form the joints between the triangular shaped panels. All this needed careful prediction of the forces at each node condition could only have been done using CAD prediction methods. Even the forming and shaping of the aluminium sunshades was possible by the use of such techniques.

Figure 7: Mock up of aluminium sunshades and their fixing to the glazing system.

FEDERATION SQUARE MELBOURNE

At Federation Square Melbourne again working with Atelier One we were struggling with translating the architects (Bates and Smart) idea for using an apparent random arrangement of stone, zinc and glass panels based on fractal geometry, we decided on a three point pinwheel to fix the panels rather like changing the wheel on a car.

Figure 8: Apparent random fractal geometry based on a pinwheel used at Federation Square.

This simple concept allowed us to translate the incredible complex structure for this multi formed facade into a complex but efficient cladding system fixed by Permastellisa Australia.

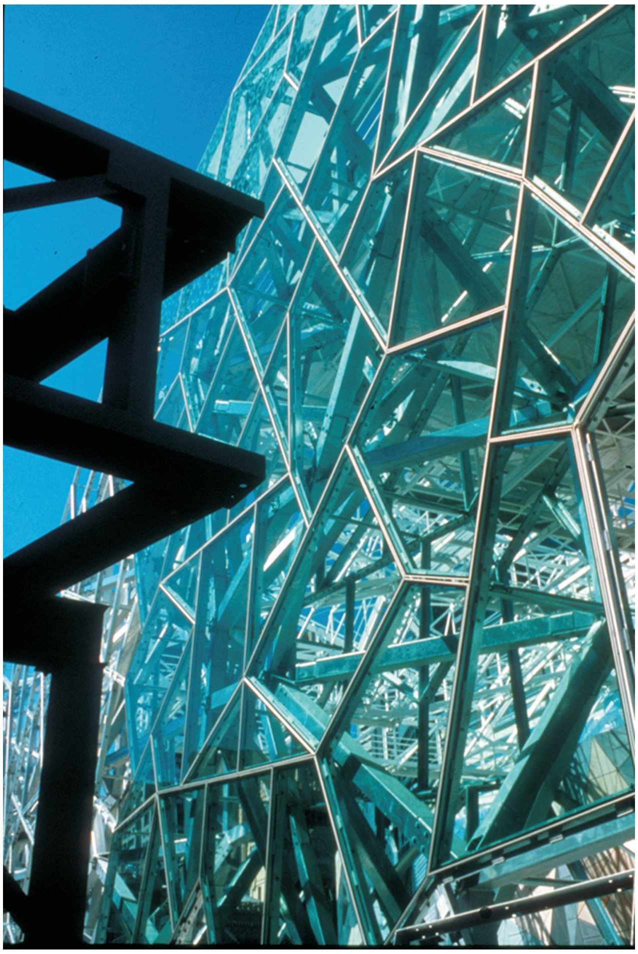

Figure 9: Complex Structure at Federation Square Melbourne (Architects Bates and Smart).

Recently in Britain there has been a re-interest in a programme of industrialized housing led by a Government Initiative (John Prescott) for low cost single family dwellings.

Unfortunately it is not likely that architects and contractors involved in this programme will look back to the lessons of the 1960's and 1970's in Britain. Each generation has to develop its own wheel.

REFERENCES

Bonshor R.B. (1972). "Component Standardisation—Graphical Aids for Manufacturers and Designer". *BRE* IN 23 /72, March. Later published as a Current paper.

Brookes A.J. (1976) Implication of change in building Technology PhD Thesis Liverpool 1976.

Bemis A.F. (1936) *The Evolving House Volume III Rational Design*. The Technology Press MIT Cambridge. Mass.

Corker E. and Diprose A. (1963) *The modular Primer*. The Modular Society London.

Eden J.F. (1967) "Metrology and the Module in Architectural Design" March 1967 p 148 also published as BRE current Paper March 1968.

Hertfordshire Architectural Dept. (1948). 'Planning of new Schools'. *Architect and Building News* 16 Jan 1948 pp 41–51.

Mac Callum I. (1959) *Architecture USA*. Reinhold, New York and Architectural Press London

Maggi P.N. (1961) "The Problem of tolerances in building". *Associazione Italiana Prefabricazione. Quaderna* 1 E 2. Milan.

Martin B. (1965) *The co-ordination of Dimensions for Building*. RIBA London.

Martin .B. (1977) Joints in Building. George Godwin, London.

Rusell B. (1981) *Building Systems Industrialisation and Architecture*. John Wiley.

Sefton Jenkins R.A. and Mak W.K. (1963) "Tolerance in Building" *Modular Quaterly* Autumn 1963.

Wachsmann K. (1961) *The Turning Point of Building: structure and design*. Reinhold Publishing Corporation New York