CCAA T38

HB71–2011 (Standards Australia)

Handbook

Reinforced Concrete Design

in accordance with AS 3600—2009

CEMENT CONCRETE & AGGREGATES AUSTRALIA

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A joint publication of

Cement Concrete & Aggregates Australia and

Standards Australia

Fifth edition July 2011

Fourth edition February 2002

Third edition May 1995

Second edition July 1991

First published September 1989

CCAA T38

HB71–2011 (**Standards Australia**)

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ISBN 978-1-877023-28-6

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CCAA is acknowledged nationally and internationally as Australia's foremost cement and concrete information body – taking a leading role in education and training, research and development, technical information and advisory services, and being a significant contributor to the preparation of Codes and Standards affecting building and building materials.

CCAA's principal aims are to protect and extend the uses of cement, concrete and aggregates by advancing knowledge, skill and professionalism in Australian concrete construction and by promoting continual awareness of products, their energy-efficient properties and their uses, and of the contribution the industry makes towards a better environment.

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PREFACE TO FIFTH EDITION

This fifth edition is a complete rewrite of the *Reinforced Concrete Design Handbook* and brings it into line with the 2009 edition of AS 3600 *Concrete Structures* and *Amendment No. 1–2010*. It also takes into account changes in other Australian Standards that have occurred since the fourth edition was published, including AS/NZS 1170 *Structural Design Actions,* Part 0 *General principles* and Part 4 *Earthquake actions in Australia*.

The 2009 edition of AS 3600 includes significant changes to:

- The maximum concrete strength covered (now includes 100 MPa)
- Development lengths and lap lengths of reinforcement
- Use of Ductility Classes N and L reinforcement
- Durability and fire requirements.

The opportunity has been taken to review many of the charts and their relevance in the modern design office. In many cases, the previous charts were nomograms from an era when these were a common design tool. These have now been largely replaced by design software or, as in this Handbook, by spreadsheets.

The spreadsheets are used to illustrate the design principles of reinforced concrete, the requirements of AS 3600 and the recommendations of this Handbook. They are in keeping with current design technology.

The spreadsheets can be downloaded from CCAA website www.ccaa.com.au/publicationextras/.

There is a new chapter covering the strut-and-tie design method to reflect the new section in AS 3600.

There are also revised rules for crack control in beams and slabs but no charts or tables are provided. However, the Design Example in Chapter 10 includes calculations showing how these requirements can be checked.

By-and-large the order in which material is presented follows that of relevant sections in AS 3600, although not all the sections in the standard are covered.

The contribution of J Woodside FIEAUST FASCE FISTRUCTE MICE, Director, *J Woodside Consulting,* in reviewing the Handbook and in the preparation of the design charts and spreadsheets is gratefully acknowledged.

CONTENTS

Chapter 1_General

1.1 INTRODUCTION

1.1.1 Codes and regulations

Designers need to understand the framework of regulations and standards within which the design of the building or structure is designed and constructed. For most buildings in Australia, the Building Code of Australia (BCA)[1.1] sets out the regulatory requirements for the building*.

The Building Code of Australia sets out Objectives, Functional Statements, Performance Requirements and Building Solutions for the various aspects of design, eg structural, and health and amenity. The first two ('Objectives' and 'Functional Statements') are broad descriptors and are used mainly to interpret the latter two ('Performance Requirements' and 'Building Solutions').

The Performance Requirements are qualitative statements, eg that under structural provisions says:

A building or structure, to the degree necessary, must:

i Remain stable and not collapse; and

ii Prevent progressive collapse; and

iii Minimise local damage and loss of amenity through excessive deformation, vibration or degradation; and

iv Avoid damage to other properties,

by resisting the actions to which it may reasonably be subject...'

** The terms 'building' and 'structure' are used to signify the same entity by administrations in Australia and in New Zealand. This may lead to some ambiguity where the terms are used interchangeably in some joint AS/NZS standards. In general, in Australia the term 'building' is used to refer to buildings—ranging from houses to multi-storey buildings—and 'structures' to refer to structures other than buildings whereas in New Zealand the term 'structure' is used inclusively to cover buildings and other structures.*

How the Performance Requirements are to be satisfied is spelt out in the Building Solutions. There are two broad approaches:

[a] Deemed-to-satisfy (DTS) solutions; and

[b] Alternative solutions.

The DTS approach involves designing the members, buildings and structures in accordance with the relevant Australian standards, eg for concrete in accordance with AS/NZS 1170[1.2] and AS 3600[1.3].

The Alternative Solution approach allows the designer to use other codes or standards, fire test data, etc. (The 2009 edition of AS 3600 omits a number of clauses from previous editions which gave rise to conflicts of interpretation with the BCA in this area, eg those that provided rules on interpretation of test data. Designers should be aware that their omission in AS 3600 does not imply that the approach is invalid but that the rules under which it is done now lie within the BCA under Alternative Solutions, not the DTS approach using the relevant Standard, eg AS 3600.)

As will be discussed later, AS 3600 provides for a number of different analysis and strength check approaches. However, the BCA and AS/NZS 1170.0 are written around a linear elastic analysis/limit states approach using characteristic strengths of the materials and factored loads.

Designers should be aware that AS 3600 provides minimum solutions, ie compliance is necessary for all buildings but particular buildings may require the application of more-stringent provisions or additional considerations/criteria to meet the client's requirements.

However, AS 3600 represents best practice even when it is not called up in the BCA and it cannot be ignored, especially where its requirements are more stringent than those in earlier editions of the standard.

1.1.2 Responsibility of designers and supervisors

The division of responsibility between the parties involved in the design and those in the construction of a building should be clearly understood and fully expressed in the terms of engagement between the owner and the designer, and in the contract for construction between the owner and the builder or contractor. 'Design' here includes the architectural and structural design of the building and the preparation of the drawings, specification, and sometimes the conditions of contract and preliminaries. Most projects will involve a number of other disciplines, eg mechanical, electrical and service engineering. Developing and documenting the final design solution will normally involve a design team covering all the required design disciplines.

The designer responsible for the structural design should be a practising civil or structural engineer eligible for Chartered Status of Engineers Australia or equivalent and experienced in the design of concrete structures of comparable importance. Architects and building graduates should not be expected to have the appropriate skills to undertake, nor should they assume responsibility for, the design of a concrete structure. Graduate engineers while working under guidance can design parts of concrete structures but they should not take responsibly for the overall design of the structure.

When designers assign the detail design of any elements to a manufacturer or supplier, they should ensure that this work is fully specified and controlled by way of detailed performance standards, and that these elements are coordinated with the structure as a whole. Examples of this are the detailed design of precast concrete elements and post-tensioned slabs.

The supervision of construction is the responsibility of the builder. All structures should be supervised by a suitably qualified person. If the structure is complex or incorporates prestressed concrete, a qualified and experienced engineer employed by the builder should be responsible for the supervision of construction.

Periodic inspection of construction on behalf of the owner or client is often undertaken by the designer, or by an experienced person employed by the owner or client but under the technical direction of the designer. Where the project is complex or unusual, a more-detailed inspection regime may be required. This arrangement facilitates the resolution, by the designer, of any queries that may arise as to the interpretation of the design documents.

Site records should be kept during construction to show the dates of concrete placing, test results, stressing details and any significant departures from the design drawings. These provide the owner with a useful record of the structure as built, should any modification be required in the future.

1.2 DESIGN PROCESS AND PROCEDURES

1.2.1 Broad structural design aims

[a] General The aim of structural design is to produce safe, serviceable, durable, aesthetic, economical and sustainable structures. Designers should always strive for simplicity, clarity and excellence in their design. Simple design does not mean elementary design but rather well conceived and quality design. As noted above, mere compliance with the appropriate codes and standards will not guarantee a satisfactory design for all buildings as they provide only a set of minimum requirements. The designer is responsible for ascertaining the appropriate criteria for the particular building and seeing that these are satisfied.

[b] Safety In service, a structure must be able to safely resist the actions (loads) expected to be imposed on it throughout its intended life. Safety must also be considered during the construction period, particularly while the concrete has not reached its design strength. Loads imposed on it during that period should be analysed as required. The design should also consider unusual load cases arising from any processes to be carried on in the structure. Some thought should also be given to the ultimate demolition of the structure.

Designers usually start with a framing plan, which is logical and sensible, and proceed to examine how that structure behaves when subjected to the various actions. In particular, they should review all possible failure modes to ensure that nothing important has been overlooked. This topic is discussed in more detail in Section 1.2.2 *The design process.*

A structure should be robust and possess structural integrity so that it is not unreasonably susceptible to the effects of accidental loads. Damage to a small area of a structure or the failure of a single element should not lead to the collapse of a large part of the structure, eg by progressive collapse. This topic is discussed in more detail in Section 1.4.6 *Structural integrity and robustness*.

The accidental hazard arising from fire is covered in building regulations, eg the Building Code of Australia. The particular requirements for different structural elements for fire resistance, eg Fire Resistance Levels to guard against structural collapse (structural adequacy), flame penetration (integrity) and heat transmission (insulation), are discussed in Chapter 3 *Durability and Fire Resistance*.

Designers must be alert to prevent gross errors during design, as these, along with those that may arise during construction, are probably the most common cause of failures. An independent check should be made of the design, including a review of the drawings and specification to ensure that the assumptions made in the design are valid.

[c] Serviceability Over its design life, during service under normal operating and load conditions, a structure must behave satisfactorily. The structure and its elements should not deflect or deform excessively or vibrate to cause discomfort to the occupants.

Any cracking or apparent distress of the concrete should not impair the structure's functionality or spoil its appearance. While some clients consider concrete to be indestructible, some maintenance and repairs of the concrete structure will normally be required during the life of the building, but this should be minimal.

[d] Durability A durable structure is one that performs its intended function over its design life in its environment without excessive degradation or unusual maintenance expense. There have been examples of inadequate durability, such as premature rusting reinforcement, spalling concrete, extensive wear and badly weathered concrete surfaces. The procedures necessary to ensure durable concrete structures are discussed in Chapter 3 *Durability and Fire Resistance*.

[e] Aesthetics An integral part of the design of any structure is consideration of its appearance. Buildings and structures such as bridges should be designed and detailed to present an attractive and well-proportioned appearance to suit their surroundings and environment. Architects rather than structural engineers are usually responsible for the appearance of buildings. However, there are many cases where the engineer can provide a significant input by the selection of appropriate framing systems and the proportioning of members to meet functional, load capacity and any aesthetic requirements.

[f] Sustainability In recent years, sustainability has become a design consideration for all structures. Sustainable design requires that social, environmental and economic outcomes are balanced. For example, a project is not sustainable if it damages the environment, or if it results in negative social outcomes such as loss of jobs or health problems, or if it results in financial loss.

Concrete is an important contributor to sustainable design. Concrete, like all products, has environmental impacts arising from the acquisition of raw materials, processing, transport and recycling at the end of its life. These are, however, significantly outweighed by the benefits that concrete delivers. Designers are referred to the CCAA's Briefings 11[1.4] and 13[1.5] and its website, www.ccaa.com.au, for further information on this topic.

Sustainable design also requires the designer to design an economical structure. Thus, the adoption of a simplistic, conservative design approach and poor detailing to minimise design costs—but resulting in an overdesigned structure—is not acceptable.

[g] Economy An economical structure contributes to limiting the overall cost of the project. This can be measured in terms of the initial cost, the construction time and the life cycle or overall cost. The low cost of concrete and reinforcement alone does not necessarily produce the most economical structure; construction and time-related costs must also be considered. Ease of construction must therefore be taken into account at the design stage.

1.2.2 The design process

The design process typically comprises three phases—conceptual design, preliminary design and final design. These are described briefly below and in more detail in Appendix A.

Since conceptual design will often be based on limited information, any structural design should be simple, quick and conservative without being heavy-handed. It is not the time for extensive computer modelling. Designers, however, need to carry out sufficient structural design to ensure that concepts are feasible.

The preliminary design phase is where the client's requirements for the project are developed in more detail. On major projects, more than one preliminary design may be produced.

The final design stage is where the design data is checked and the chosen optimum design is developed and detailed. This will include the preparation of project documentation and specifications. It is important for the designer to remember that the documentation is the means of communicating the design intentions to the contractor/builder and subcontractors. The documentation should be reviewed from this viewpoint before being issued.

There are a number of overseas manuals[1.6,1.7,1.8] on the design of reinforced concrete buildings to which the designer can refer for further information and guidance.

1.2.3 Order of design

The building should be designed in a logical order for analysis and drafting. For an office building the order of design might be as follows:

- Establish the design loads (AS/NZS 1170)
- Confirm the design data such as: survey, geotechnical, environmental, etc
- The occupancy of the structure, required fire ratings, sound transmissions, etc from the BCA, (normally provided by the architect)
- Establish exposure classification and durability requirements including concrete strength(s), cover(s) and axis distances, deflection criteria (AS 3600)
- Establish any other special design requirements
- Lateral stability for wind and earthquake loadings and general stability in two orthogonal directions
- Roof framing including slabs and beams
- Plant room slabs and beams
- Typical floor slabs and beams
- First floor and non-typical slabs and beams
- Ground floor slabs and beams

- Basement floor slabs and retaining walls
- Stairs and lift cores including lift motor rooms
- Column and wall load rundowns
- Column and wall designs
- Footings and foundation capacity
- Precast or external walling
- Robustness check and detailing
- Other architectural elements that may require structural design
- Checking and review of drawings and specifications.

1.2.4 Structural framing

Finding the best structural framing solution for a building is not straightforward and there will typically be alternative solutions. The framing must consider how all the loads find their way through the structure, both horizontally and vertically, to the footings. Framing is a trial-and-error process and adjustment will need to be made as the design proceeds. The process is neither taught nor covered in textbooks and requires a good appreciation of architectural and engineering constraints.

Concrete structural frames are commonly used in Australia and have the advantage of good performance in fire. They can be cast in situ, precast or both. The frame for larger projects usually needs to be modelled for input into the computer for analysis. Which members are pinned and which are continuous also need to be established.

Certain buildings lend themselves to standard solutions, eg an industrial building or shopping centre. Local conditions will sometimes favour different solutions depending on the local building industry capability, etc. Column/wall locations are often dictated by the intended use of space. For example, for a car parking building the column spacing must suit parking bay sizes; for an office building a column-free space may be required or there may be other spatial requirements developed by the architect from the client's needs.

The floor-to-floor height also needs to be considered and the space required for building services, particularly in the space under the floor and above the ceiling. Concrete allows efficient floor solutions, minimising the overall height of a building or maximising the number of floors in a given height.

Designers also need to define how lateral loads are resisted, suitable systems can include one or more of shear walls, moment-resisting (space) frames and cantilever columns or walls.

Assessing, apportioning loads and understanding the load paths can be difficult to appreciate. The assessment of all loads is one of the fundamental design considerations before commencing final analysis and design. If the loads are wrong or apportioned incorrectly, they will affect the design of all members, and extensive rework and extra time will be involved—assuming the errors are found—or, if the errors are not found, possibly an unsafe structure.

1.2.5 Initial estimation of member dimensions

The initial estimation of member sizes is generally based on past experience, some quick trial designs or other design information. Design offices may have design guides based on experience of successful designs and recommendations where problems have arisen.

The depth of flexural members is usually controlled by deflection considerations. The minimum thickness of walls tends to be governed by construction and cover considerations, and this is also true for column dimensions. The axial load capacity of columns can be significantly increased by increasing the concrete strength and/or increasing the longitudinal reinforcement percentage. Neither of these necessarily increases the column dimensions. However, lateral load bending moments and limiting sway movements may dictate some minimum dimensions.

1.3 DESIGN CHECKS AND METHODS OF ANALYSIS

In a real structure, the behaviour under load of individual elements can be complex, depending on the materials used and many other factors. Generally, idealised models of the frame or structure are developed to analyse how the real structure may behave.

The analysis that is carried out to validate a design is generally a two-step process although some computer programs may combine the two steps:

- Structural analysis of the frame or structure
- Strength check and other design checks at critical cross-sections of members.

The first step of analysis is aimed at determining the action effects such as bending moment, shear force, torsion and axial force at critical sections of members necessary for strength design or determining deformations of the structure. The second step is concerned with the strength check of these critical sections along with other design checks such as deflections.

AS 3600 makes provision for a variety of methods to be used for strength checks, viz:

[a] Procedure for use with linear elastic analysis methods of analysis with simplified analysis methods and for statically determinate structures (see AS 3600 Clause 2.2.2).

[b] Procedure for use with linear elastic stress analysis methods (see AS 3600 Clause 2.2.3).

[c] Procedure for use with strut-and-tie analysis (see AS 3600 Clause 2.2.4).

[d] Procedure for use with non-linear analysis of framed structures (see AS 3600 Clause 2.2.5).

[e] Procedure for use with non-linear stress analysis (see AS 3600 Clause 2.2.6).

In addition, it is permissible to carry out design checks for strength and serviceability by testing a structure or component member in accordance with the requirements of Appendix B in AS 3600 (see AS 3600 Clause 2.1.1).

The first of these procedures, (a), is the one which will be familiar to most designers and was in earlier editions of AS 3600. The other methods have been introduced into the 2009 edition of AS 3600 to permit the use of more-sophisticated computer-based analysis programs, eg Finite Element Analysis. Foster[1.9], while Foster et al[1.10] give a summary of the other methods, (b) to (e), and indicate where each may be applicable and the provisos associated with their use.

Designers should be aware that there is conflict between these latter methods, (b) to (e), and the requirements in the BCA and AS/NZS 1170.0. For example, BCA (Volume 1) BP1.2 mandates use of 5% characteristic material properties and this would preclude the use of some structural check procedures in AS 3600, eg non-linear analysis of framed structures which uses mean values of material properties. AS/NZS 1170.0 called up by the BCA is written around the linear elastic method of analysis and ultimate limit states approach. For example, see Section 2 in that Standard. This may or may not be a problem. However, strut–and–tie analysis may be the only appropriate method of design for non-flexural members.

This Handbook is written around the method in (a) which is compatible with both the BCA and AS/NZS 1170.0. No conflict is therefore foreseen with the following discussions, except perhaps for Chapter 9 *Strut-and-tie modelling*.

1.4 LIMIT-STATES DESIGN AND DESIGN CHECKS USING LINEAR ELASTIC METHODS OF ANALYSIS

1.4.1 General

A limit-states approach to design is assumed by the BCA and AS/NZS 1170.0. The procedure for use with linear elastic analysis methods and for statically determinate structures given in AS 3600 Clause 2.2.2 is compatible with this approach.

Limit-states design assumes there will be an acceptable probability that a structure designed and built in accordance with the Standard will not reach any limit state during its design life. That is to say, it will not fail by collapse or instability (ultimate limit states), or become unfit for service by deformation, vibration or cracking (serviceability limit states). In addition, the structure should not deteriorate unduly during its design life and should not be damaged by events such as fire, explosions and impact to an extent disproportionate to the cause. A checklist of design requirements includes:

- Stability
- Strength
- Serviceability
  - Deflection
  - Lateral drift (eg under wind or earthquake)
  - Cracking
  - Vibration
- Durability
- Fire resistance
- Structural Integrity/robustness (prevention of progressive collapse)
- Other limit states as required.

Limit-states design analyses the structure or part for the relevant combination of factored actions (the action effect). It then confirms that the design capacity, ie the nominal capacity multiplied by the capacity factor (capacity reduction factor), ϕ, exceeds the action effect. (The use of a global factor rather than partial safety factors, as adopted in European standards, follows the practice established in ACI 318[1.8] and that used in earlier editions of AS 3600.)

In essence, following this approach, the steps in design for the ultimate limit state are (the design for serviceability limit states is similar):

- Determine the actions on the structure
- Determine the appropriate combinations of actions
- Analyse the structure for the applied combinations of actions
- Design and detail the structure for robustness and earthquake