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THE NEW ZEALAND LOADINGS CODE AND ITS APPLICATION TO THE DESIGN OF SEISMIC RESISTANT PRESTRESSED CONCRETE STRUCTURES

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1. INTRODUCTION

In New Zealand the design of normal buildings (as distinct from more special structures such as bridges, towers, dams, major storage tanks, etc.) is governed by the requirements of NZS 4203 "Code of Practice for General Structural Design and Design Loadings for Building" [1]. The Code was published earlier this year and is the result of a revision effort which commenced in June 1970. It is of interest that the code will now be subject to "on going" review and is to be updated as required on a regular yearly basis.

The loading code sets down the minimum design requirements which should "provide a reasonable level of protection to life and property of an economic level of cost taking into account the relative seismicity of New Zealand as compared with the rest of the World and the particular building practice and design methods adopted in this country". [1]

This paper briefly summarises requirements of the Code which apply to the design of prestressed concrete structures.

The views expressed are the personal views of the Author and do not necessarily represent the views of the Code Committee.

2. THE CODE

The code is deterministic in type and is based upon the use of the strength method of design. If anything it could be said to be oriented towards design in reinforced concrete.

The code is in four parts:

Part 1 General
Part 2 Dead Live and Snow Loads
Part 3 Earthquake Provisions
Part 4 Wind Loads

Only the earthquake provision and related requirements will be discussed in this paper.

The design load equations for combinations of loading applying to the strength method are set out on page 12, Ref. 1. The equations are based upon those given in ACI 318.71[2] with one or two changes. The most important being that a load factor is not applied to the earthquake load and its related effects.

A reduced gravity load W_t is used for the purpose of calculating horizontal seismic forces.

The Code continues the zoning provisions from the previous code [3] which divide New Zealand into three earthquake zones A, B & C.

The code earthquake provisions are based upon the assumption that during its lifetime a building in Zone A will experience one or more earthquakes of high intensity and long duration together with several earthquakes of moderate intensity and duration. It is further assumed that the risk of such events is less in Zone B and least in Zone C.

At the present state of the art it is not practicable to determine an exact and unique seismic ground motion for a particular building on a given site.

The code therefore provides for the use of two basic methods of analysis, either the equivalent static force method or a spectral modal analysis. The spectral modal analysis may be supplemented by a further dynamic analysis such as a numerical integration response analysis.

The minimum load levels from the equivalent static force method are used to calibrate the results of the dynamic analysis.

Seismic forces for both methods are determined from an idealised trilinear response spectrum given in the Code. The spectra incorporates the modifications necessary for soft soils and the zoning provisions.

The earthquake provisions of the code are discussed in more detail by Kolston [5].

3. CODE PHILOSOPHY & DESIGN PRINCIPLES APPLYING TO THE EARTHQUAKE PROVISIONS

3.1 General

The code philosophy at least for those structural types with a good earthquake history is based upon the principle that the energy resulting from building response to the earthquake shaking is absorbed and dissipated by inelastic deformation in a selected and controlled manner. In terms of the code "Buildings shall be designed to dissipate significant amounts of energy inelastically under earthquake attack." [1] For normal structures economics will usually preclude a purely elastic response. For particular members several excursions into the inelastic range can be expected during an earthquake.

The function of materials codes is to ensure that the structural material used when properly designed and detailed can provide the necessary capacity to absorb and dissipate energy in accordance with the

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design principles of the Code without an undesirable brittle type failure occurring such as failures due to shear or instability. This ability has come to be loosely termed "ductility".

For structures with 'reduced' ductility the code applies more severe requirements while for small buildings of 'limited' ductility either elastic or low inelastic demand design procedures may be used. Code philosophy and design principles are discussed in more detail by Glogau [6].

3.2 Ductility

The previous loading code [3] although based upon the use of structures displaying good ductility made only vague references to such requirements.

The code attempts to differentiate between 'adequate' ductility required for ductile structural types with S factors between 0.8 and 1.2, the ductility (reduced) associated with systems which dissipate energy in a shear mode and the 'limited' ductility type small buildings mentioned above.

The commentary Clause C3.2 gives some guidance to designers on what is meant by 'adequate' ductility and sets down the number of excursions into the inelastic range which the structure must be capable of sustaining and the magnitude of the deformations together with the acceptable associated loss of strength for the structure. Additional requirements apply to displacement and curvature ductility demands on members.

3.3 Capacity Design

The code introduces the principle of capacity design in which "energy-dissipating elements or mechanisms are chosen and suitably designed and detailed and all other structural elements are then provided with sufficient reserve strength capacity to ensure that the chosen energy-dissipating mechanisms are maintained throughout the deformations that may occur" [1]. The state of the art is such however that there are considerable differences of opinion on methods of determining upper and lower bounds of strength of individual members, the distribution of beam capacity moments into columns, axial loads induced in columns by the simultaneous formation of beam hinges design of panel zones or joints in beam column junctions, to name just some.

The problems apply equally to all structural materials used in ductile frames. Structural steel, reinforced concrete and prestressed concrete.

3.4 Structural Systems

The code includes the design principles for achieving the objective of dissipating significant amounts of energy inelastically in both frames, walls and diagonally braced systems. Column hinge mechanisms as distinct from limited column hingeing are permitted only in single or two-storey structures and in the top storey of a multi-storey building.

In the case of shear walls the code identifies three groups of wall:

(a) the ductile coupled shear wall
(b) the ductile cantilever shear wall, and
(c) cantilever shear walls not designed for ductile flexural yielding.

4. SPECIFIC CODE PROVISIONS APPLYING TO PRESTRESSED CONCRETE

4.1 General

The provisions of the Code apply generally to all structural materials but certain requirements apply to particular materials. In the following sections those relating to the use of prestressed concrete are discussed.

4.2 Values of Cd

Clause 3.4.2 of the Code provides the means of determining the total horizontal seismic force V acting on the building. V is related to the gravity load Wt on the structure by the familiar formula V = Cd Wt where Cd = CISMR.

The basic seismic coefficient C is obtained from the idealised spectrum response spectra given in Fig. 1 for the particular building period, zone and soil type. The importance factor I allows the use of higher load levels for buildings which are regarded as more essential to the community in the event of an earthquake and therefore the risk of damage should be reduced. Values of I are 1.6 for essential facilities (Class I), 1.3 for public buildings and 1.0 all other buildings. Values of the structural type factor S are given in Table 5, Ref. 1, for the various structural systems. It is important to note that the Code places no restriction on the combination of S factors applying to buildings with different structural systems for each direction under consideration. This approach differs somewhat from overseas codes. For instance SEAOC 1973 [4] p51 states that if "a building requires a K = 1.33 in one direction then K = 1.33 shall apply in the other direction". The case of a combination of structural types in a particular direction or in the height of a building is more difficult and little assistance is given by the Code. This aspect is currently under consideration by the Code Committee.

The structural material factor M is intended to reflect the record of performance of the material when used in various structural systems subjected to earthquake shaking. Values of M given in the Code appear in Table 6, Ref. 1. For prestressed concrete a value of 1.2 is specified and applies to "elements which resist seismic forces and movements by flexural yielding". Such a requirement would cover structural types Items 1-5 being those with S factors 0.8 - 1.2, i.e. ductile frames, ductile coupled shear walls, ductile cantilever shear walls. The code does not give a clear guide on the use of prestressed concrete in other structural systems, e.g. for shear walls not designed for ductile flexural yielding or for improvement of the performances of other structural materials such as the joints of reinforced concrete members. Under such circumstances it would be reasonable to use the structural material factor applying to the primary material.

It is important to note that the caveat included in the Code p33 which is reproduced in full below.

"The value of M = 1.2 when used in prestressed concrete ductile frames should at this stage be regarded as tentative and subject to review when sufficient response analyses of multistorey structures subjected to a range of earthquake motions have been made; the increase of 20% above the value for reinforced concrete is intended to allow for the increased response of prestressed concrete structures.

At the present (1975) state of knowledge some authorities are by no means agreed that prestressed concrete is an entirely satisfactory material for use in ductile frames and shear walls. For instance SEAOC 1973 comments as follows:

"The use of prestressing to develop ductile moment capacity will require testing and is the subject of future study. Other members within the building, not part of the space frame, may be precast, prestressed composite, or any other appropriate system if adequate diaphragms and connections are developed so the building will respond to seismic input as a unit."

Other authorities are concerned at the extent to which concrete crushing and joint deformations are required to dissipate seismic energy.

Designers are urged to adopt a conservative approach until more evidence on response and performance are available. For design and detailing requirements designers are referred to the 1976 recommendations of the N.Z. Prestressed Concrete Institute."

The material factor is quite complex and covers a number of performance characteristics. For instance in the case of reinforced masonry the increased M factor would tend to cover the extent to which performance relies (more so than other structural materials) on the standards of workmanship on site. For prestressed concrete it is intended to take into account to some extent the increased response of a prestressed concrete structure relative to a reinforced concrete frame of equivalent strength and elastic stiffness. This aspect is discussed further in sections 4.3 and 5.

The resulting Cd values for a Class III building with a ductile frame of prestressed concrete in Wellington (Zone A) and Auckland (Zone C) for soils which are soft and also intermediate and hard are shown in Fig. 3 of Ref. 1. Plotted also for comparison are equivalent maximum and minimum Cd values from the SEAOC 1974 [7] provisions (see fig. 1 of this paper).

Of interest is that the SEAOC values are almost entirely contained within the curves of Zone A soft soils and Zone C hard soils.

The equivalent Cd values of the SEAOC recommendations have all been dramatically increased by the 1974 provisions. For instance at a period of 0.5 secs. the maximum value has been increased by a factor of 2.22 and for the minimum value by 1.76.

4.3 Deformations

Clause 3.8 of the Code requires the use of a modification factor D for computing deformation due to earthquake loads. The basis for clauses in the Code on deformations is discussed in greater detail by Blakeley [8].

As stated in the commentary the deformation modification factor for prestressed concrete structures is based on a limited amount of work done to date on their response and the provision corresponds to a 40% increase relative to reinforced concrete structures with the same initial stiffness. In comparing prestressed concrete and reinforced concrete structures it was assumed that damping for ductile frames was 2% and 5% respectively and for ductile cantilever walls 5% and 10%. The higher damping values for reinforced concrete arise due to earlier cracking of that material.

5. THE STRUCTURAL MATERIAL FACTOR FOR PRESTRESSED CONCRETE

The original draft of the Code sent out for comment in 1973 did not include a material factor for prestressed concrete. Further the commentary contained the statement that material factors "for prestressed concrete will be given when more work has been done on response and detailing and when viable earthquake performance records have been obtained". This statement summed up the reservations that a number of members of the Code committee had on the behaviour of a prestressed concrete structure subject to earthquake shaking. These doubts were shared by a number of knowledgeable people both in New Zealand and overseas and reflected in such important seismic recommendations as SEAOC 1973 [4].

A number of important matters were discussed at length by the committee before arriving at the decision. These were:

1. The lack of an adequate New Zealand or overseas code or recommendation for the ductile detailing of prestressed concrete in structures to resist earthquake shaking.
2. The absence of performance records and practical experience covering properly detailed fully prestressed concrete structures subjected to real earthquakes.
3. The lack of research on the response of prestressed concrete frames to actual earthquake records apart from El Centro 1940 N-S. It was suggested that the response to other earthquake records such as those with more sinusoidal characteristics could give greater amplification of response.

   In addition little information was available on the damping characteristics of prestressed concrete buildings.

4. The increased difficulties in applying a capacity design approach to a prestressed concrete structure to ensure that undesirable structural mechanisms did not form.
5. The view that without non-prestressed

steel, energy dissipation occurs only as a result of crushing of concrete and not as a result of yielding of steel.

6. The possibility that unbonded tendons could be used in a frame.
7. The difficulties in repairing structural damage to prestressed concrete members.

During consideration of the comments on the draft the Committee's attitude to prestressed concrete was influenced by two important developments. These were:

1. The active steps taken by the Seismic Committee of the NZPCI to produce recommendations for the design and detailing of ductile prestressed concrete frames. The recommendations were recently published in the bulletin of the New Zealand National Society for Earthquake Engineering [9]. Hopefully the recommendations will now be subject to "design office exposure" and resulting refinement and clarification with a view to becoming a code of practice in the near future.

2. Research on the response of prestressed concrete frame structures has been extended to the use of other earthquake records such as Jennings A2 artifical earthquake record which models the ground earthquake shaking adjacent to a fault in a magnitude 8 or greater earthquake and has a spectrum intensity 50% greater than El Centro 1940. These have confirmed that the maximum displacement of the fully prestressed concrete frame was on average 1.3 times that of a reinforced concrete frame with the same strength initial stiffness and damping. There was, however, significant variation from the average value the range being 0.7 - 2.4.

The earlier research reported by Blakeley and Park [10] on single degree of freedom and multi-storey structures used the El Centro 1940 NS earthquake record. This indicated that a prestressed concrete structure had a maximum displacement approximately 1.4 times that of a reinforced concrete frame with the same strength initial stiffness and damping. In fact differences in damping are likely between reinforced and prestressed concrete. However, the prestressed concrete structure will usually be more flexible and thus any increased response due to reduced damping counteracted.

Such considerations led to a decision to adopt a structural material factor M of 1.2 which is a 20% increase in the design earthquake load for prestressed concrete over that for reinforced concrete.

The value of M = 1.2 is regarded as tentative and subject to review when further research information becomes available from response analyses for other earthquake ground motions and hopefully reports on the actual behaviour of prestressed concrete structures subject to earthquake shaking.

In addition the caveat discussed earlier was included in the final version of the Code.

6. CONCLUSIONS

As has been stated on a number of occasions, experience has shown (and particularly in Japan) that even high levels of seismic forces in codes will not guarantee good or even adequate performance of a structure subject to earthquake shaking. In order to achieve a tough, ductile structure with good performance characteristics careful attention must be paid to structural concept, detailing and quality of construction and materials no matter what structural material is used.

In my opinion, if the provisions and intent of NZS 4203 together with the detailing recommendations of the Seismic Committee of the NZPCI are followed, prestressed concrete will give good performance characteristics to buildings subjected to earthquake shaking.

7. REFERENCES

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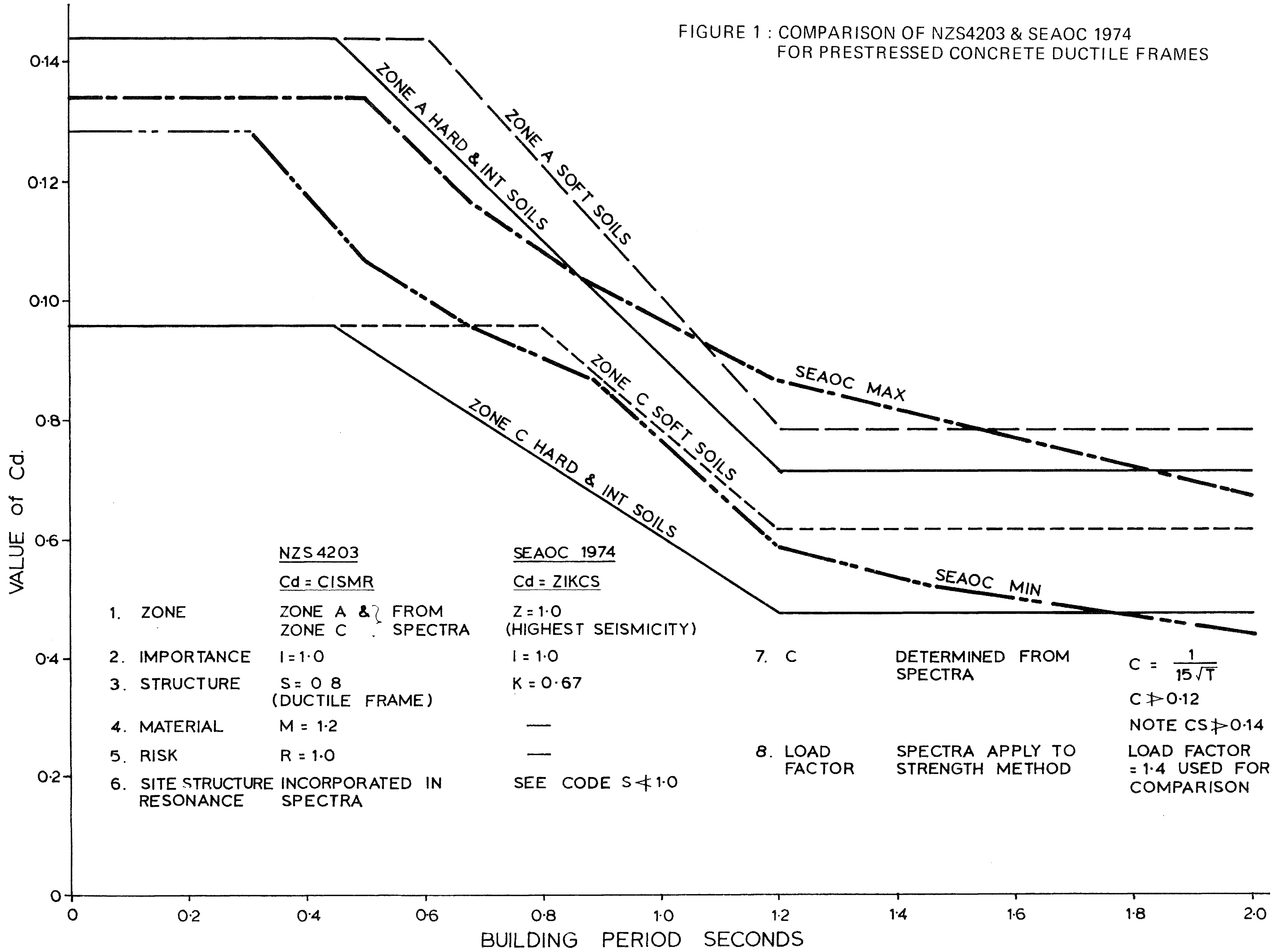

FIGURE 1 : COMPARISON OF NZS4203 & SEAOC 1974 FOR PRESTRESSED CONCRETE DUCTILE FRAMES