TORSIONAL PHENOMENA ANALYSIS AND CONCRETE STRUCTURE DESIGN

By K. G. TAMBERG and P. T. MIKLUCHIN

The analysis of structures with respect to torsion is discussed by considering the interrelationships between applied loads, types of structure, generated forces and moments, and resulting stresses. It is emphasized that torsional analysis requires that a distinction be made between solid and thin-walled members and that it is an integral part of the overall structural analysis process. The state of the art of analysing structures in which torsion is generated is established by referring to existing literature, pertaining to theoretical and experimental methods of analysis, important theoretical formulations, and practical analysis results.

The analysis of concrete structures using methods based upon elasticity is discussed. The importance of employing model and field testing in the analysis of structures, and the augmenting aspects of theoretical and experimental methods are elaborated upon. The need for further research is stressed in order to clarify the behavior of concrete structures subjected to torsion and to furnish data for the analysis and design of such structures.

It is proposed that clauses pertaining to the problem of torsion be incorporated into existing engineering codes of practice, making distinctions between the behavior of solid and thin-walled type constructions as appropriate.

Keywords: cracking (fracturing); creep properties; deformation; *elastic analysis*; flexural strength; loads (forces); models; prestressed concrete; reinforced concrete; shells (structural forms); shrinkage; structural analysis; *structural design*; structural forms; *torsion*.

☐ Employing concrete, the engineer is now able to design structures of virtually any desired shape to meet requirements imposed by a wide range of conditions of use, applied loads, and aesthetics. It is now possible to create forms of great structural efficiency and architectural beauty. The conception and utilization of structures which more fully take advantage of the ability of reinforced and prestressed concrete to resist complex stresses requires an explicit consideration of torsional effects. In certain types of structures torsion is of paramount importance.

The approach adopted in this presentation is to identify how the occurrence of torsion relates to the overall process of design, of which the process of analysis is an integral part. It is indicated that both theoretical and experimental methods of analysis are part of the arsenal of methods at the disposal of the engineer.

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Considering theoretical methods, however, it is emphasized that classical elastic analysis still dominates. Present theoretical procedures assume that structures behave elastically, since limit design and stochastic procedures have not yet been developed to sufficient generality that they constitute alternatives. Therefore, only methods of analysis based on the elastic behavior of structures need consideration.

Structures are grouped according to their torsional behavior, revealing that a large variety of structures develop torsional stresses. Torsional phenomena must be analysed in the context of the general problems of static and dynamic equilibrium and stability. Methods which permit the elastic analysis of structures over the full range of torsional behavior, embracing warping, Saint-Venant and mixed forms of torsion must be used as appropriate, and can be modified in many cases to consider effects of cracking and creep. Since model analysis and field testing complement theoretical methods in the analysis of structures, they are briefly discussed. Practical examples are presented to illustrate effects of torsion.

Although further research must be undertaken to clarify the torsional behavior of both reinforced and prestressed concrete structures, the information presented in this paper together with the material in the references quoted ought to permit the reader to acquire an insight into the principles of a rigorous approach when analysing structures subjected to torsion. No timidity need be shown by the engineer in the torsion-oriented analysis of structures, in view of the analytical and experimental methods of analysis available.

THE PROCESS OF DESIGN AND TORSION

Design of structures is a creative process. It is an art and science of searching for an ideal structural form in response to an expressed need or desire, and in harmony with social goals and individual objectives, applied loads, materials, framings, and methods of construction. Design thus entails a sequence of decisions and actions which lead to structures which can be built at some point in time.

This paper is concerned principally with torsion as it may have to be considered as part of the design process. Whether a structural unit* is subjected to torsional action depends upon types of applied loads, materials, framings and methods of construction. The severity of that torsional action depends on the action of the loads in relation to the geometry, physical properties, and boundary conditions of the structural unit, as well as the modes of connection and structural behavior of adjacent units connected to it. The deformations and stresses resulting from that torsion must be considered in conjunction with those generated by axial load, shear, and flexure in order to establish resultant stress effects which the unit must be capable of resisting.

In order to design an adequately performing structure, then, the structural engineer must understand how loads act on a structural unit and how the unit behaves under the specified loading. With such understanding, he can use his ingenuity and knowledge of structural framing systems to reduce or avoid undesirable load effects. For example, he may conceive systems to minimize torsion, if he is uncertain of the generated structural response when a unit is subjected to torsion. On the other hand, it has been found that the mobilization of the torsional strength of structures can effect significant savings in total costs. Excellent examples of this effect are provided by modern bridge, viaduct, and shell type structures, and as a consequence the structural engineer must now consider explicit effects of torsion in the process of structural design and analysis. The aim of this paper is to gather together the best of the available information and to place it in perspective. In the past, many engineers have shown great reluctance in attempting to deal with problems of torsion because of conservativeness of methods of design used and the scarcity of information available.

The process of designing structures is however subject to continuous development, and the ultimate proof of the adequacy of a design is its performance measured in terms of the total cost incurred to the owner and society. Progress made in design methodology takes place through the continual interaction between the various phases of design, construction, performance and research as depicted in Fig. 1-1. The process of design, its component parts and their

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*The term structural unit is used in this paper to designate any component part of a structure, or the entire structure, depending on which is under consideration.

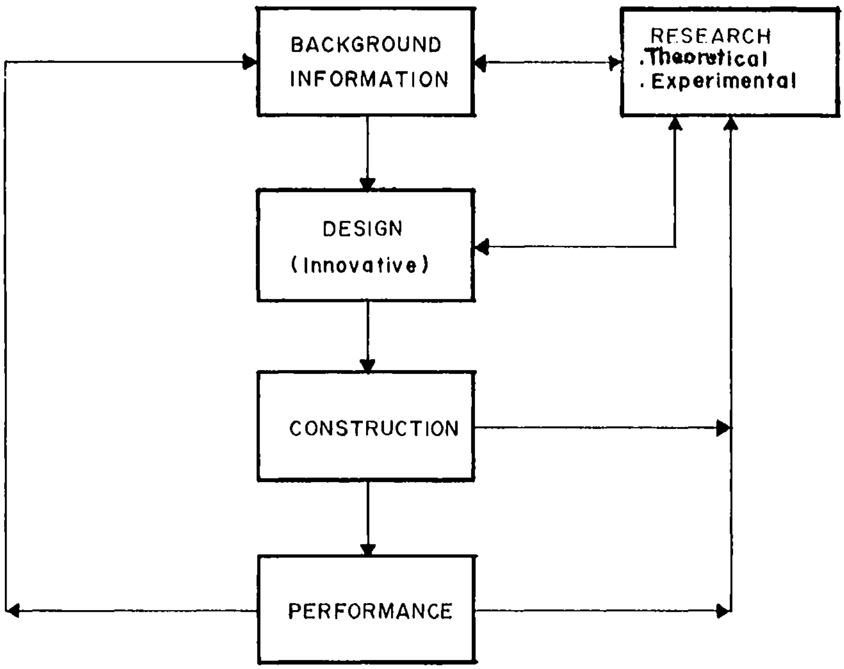

Fig. 1-1 – Development of structural design

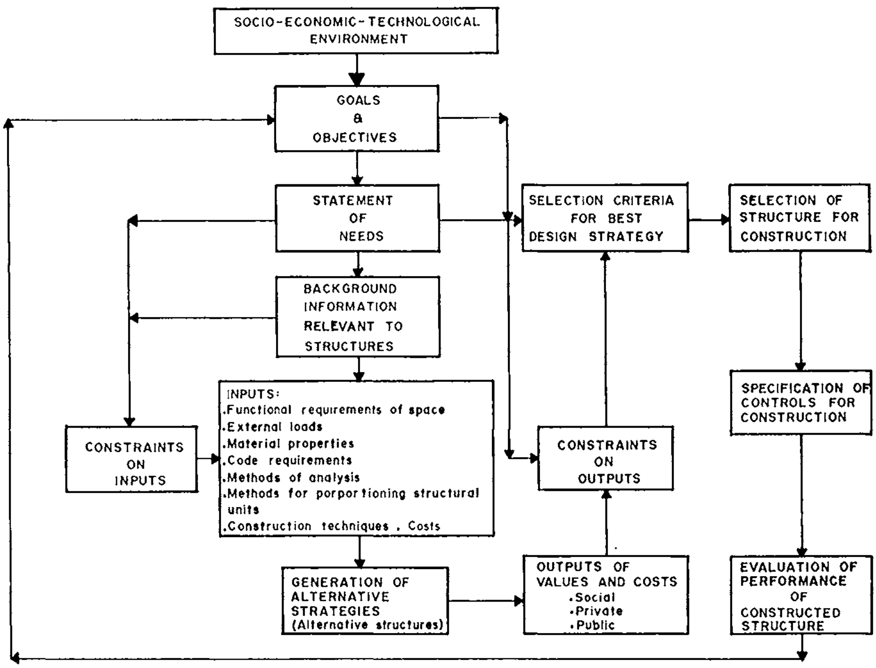

Fig. 1-2—Process of design

interrelationships, can be described as shown in Fig. 1-2. Although many variables influence design, it should be understood that the essential contribution of the structural engineer to the conception and realization of satisfactory structures of functional and aesthetic form is to minimize costs of design, construction, and maintenance while maximizing benefits. An integral part of the process of design therefore is structural analysis which can be described as shown in Fig. 1-3. It is indicated there that the designer may resort to either analytical or experimental methods of analysis, or a combination of both.

The logistics of analysis and proportioning of concrete structures is outlined in Fig. 1-4. As shown there, the methods of analysis based on limit strength and on stochastic principles have not reached the same state of development as the classical elasticity-based methods. The engineer, therefore, is presently restricted to elastic analysis and, for certain structures, to ultimate strength design.

The 1960's were a period of intensive research on torsion. A large number of publications appeared, covering primarily the areas of elastic analysis and design. ACI Committee 438–Torsion has encouraged the undertaking of research, has scrutinized and digested available information on the proportioning of concrete subjected to torsion, and has published tentative recommendations[1] for the ultimate strength design of reinforced concrete members to resist torsion. With this latter document as a reference, ACI Committee 318 has incorporated provisions for combined torsion and shear for straight non-prestressed members, in the ACI 318-71 building code requirements for reinforced concrete.[2] T, L, I, and closed compact single-cell, rectangular, hollow box-sections are considered. No provisions have yet been furnished to cover non-rectangular or multi-cellular box sections or other open type cross-sections, apart from the fact that prestressed concrete construction is not covered. The information with respect to effects generated by warping, axial forces, creep, and the dynamic application of loads is not complete. Data relating to torsional rigidities which should be used to determine torsional moments in structures is scant. It is expected that future research will fill in missing information and that ultimate strength criteria will become available to cover a wider range of structures. It is noteworthy that imaginative design engineers, using elastic methods of analysis, meanwhile have succeeded in the design of bridge, viaduct, and shell type structures which are subjected to torsion,[3] notwithstanding these gaps in information. It is worth mentioning that theoretical elastic methods can be extended to cover creep, if creep is viewed as a delayed elastic response to stress.[4]

It should be noted also that the applicability of theoretical methods of elastic analysis can be enhanced by resorting to experimental model analysis[5] and field testing.[6] Specific structures can be tested and test information can be incorporated to modify analytical procedures. For example, the behavior of concrete structures is significantly affected by the reinforcing provided. If cracking occurs, a significant reduction in both the flexural and torsional rigidities takes place which redistributes internal forces; this may influence the proportioning of reinforcement in structures such as spandrel beams[7,8] and grids.[9] Consequently, reduced flexural and torsional rigidities, determined by experimental methods, can be used in the elastic analysis procedure. On the other hand, model analysis can be used exclusively to design specific structures.[9]

STRUCTURES SUBJECTED TO TORSION

To put then the problem of torsion into further perspective, the interrelationships between applied loads, types of structure, generated internal forces, deformations, and dynamic behavior are considered next in qualitative terms. Fig. 1-5 is intended to show that structures which are subjected to loads and contain varieties of materials, employing various framing systems and methods of construction, can be categorized into three main types: A, B, and C, as is shown in column 4. Of these, types A and B are of special interest. That is, type A embraces structures which may be considered to consist of single structural units resisting torsion; for example, a beam or shell unit. In turn, type B embraces structures consisting of component parts resisting torsion, such as, for example, a space frame or grid-type structure. It is indicated that axial, shear, flexural, torsional stresses and deformations, and their various combinations must be considered, as appropriate, in order to allow prediction of the behavior of structures in their stressed state. It is clear that the degree of importance of torsion for concrete structures may vary widely, but it must be correctly estimated to permit rational design.

The problem of structural analysis involves the establishment of behavioral characteristics and associated structural constants for individual structural units of various types, support and boundary conditions, and the analysis of complex structures in the light of individual unit behavior.

Fig. 1-6 shows basic forms of structures of type A. It is possible to conceive of a large number of different configurations which consist basically of singular structural units having differing alignments, support and boundary conditions, and cross-sections. Such structures occur in the construction of bridges, viaducts, and buildings. Fig. 1-7 shows some structures of type B, each of which may be conceived as containing individual structural units.

Referring to types A and B it is now possible to identify another type categorization which distinguishes between structures with open thin-walled cross-sections and those with solid, compact, bulky-type cross-sections (Fig. 1-8). Depending upon the types of cross-sections encountered, lengths of span, modes of support, and boundary conditions, analysis may range from elastic warping torsion theory to the classical Saint-Venant torsion theory. For a large number of frequently occurring structures, modified versions of these theories for mixed torsion, accounting for both warping and Saint-Venant torsion effects, must be used if an analytical analysis is to yield reliable estimates of torsional stiffness, deformations, normal and shear stresses, and deflections. Analysis of thin-walled sections, either open or closed, or of open-closed types, must also take account of the effects generated by changes in the geometry (distortion) of cross-sections. In addition, effects due to cracking, temperature, shrinkage, and creep must be determined, if significant. By the proper incorporation of warping and Saint-Venant torsion effects into the elastic analysis procedure, the practical analysis of many structures becomes possible.

The relative importance of the warping and Saint-Venant torsion effects is initially demonstrated by referring to three cases of simply supported beams,

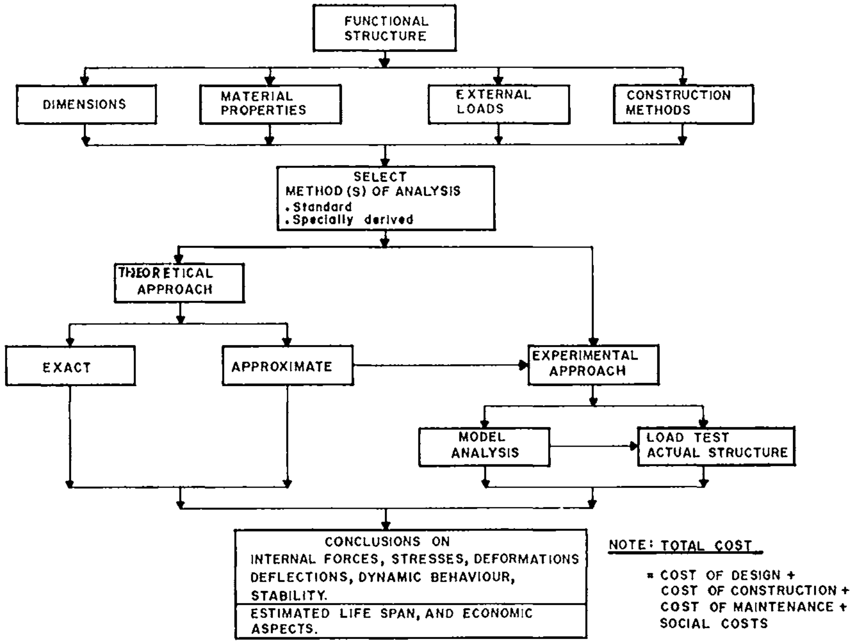

Fig. 1-3—Process of analysis for structural design

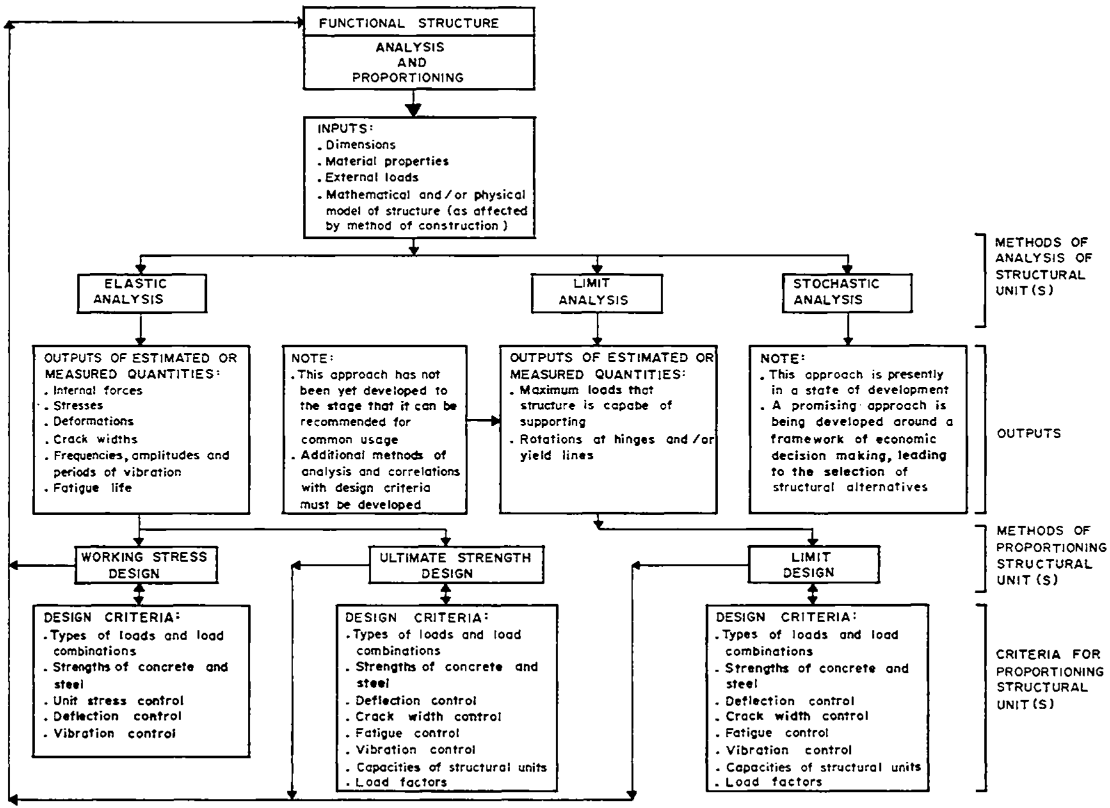

Fig. 1-4—Logistics of analysis and proportioning of concrete structures

STRUCTURES SUBJECT TO GENERALIZED TORQUE						
LOADS WHICH DETERMINE GENERALIZED FORCE FIELDS	STRUCTURE		CATEGORIZATION OF STRUCTURES FOR PURPOSES OF EVALUATING TORSIONAL EFFECTS	ESTIMATE QUANTITIES FOR DESIGN OF STRUCTURES DUE TO ACTION OF GENERALIZED FORCE FIELDS		
	MATERIAL	METHOD OF CONSTRUCTION		INTERNAL FORCES	DEFORMATIONS	VIBRATIONS
D - dead load SD - superposed dead load L - live load LF - longitudinal force from L CF - centrifugal force W - wind load on structure WL - wind load on L EQ - earthquake SF - stream flow pressure ICE - ice pressure E - earth pressure B - buoyancy S - shrinkage C - creep T - temperature F - longitudinal force from friction R - rib shortening BL - blast load	Plain concrete Reinforced concrete Prestressed concrete (pre and post-tensioned) Ferro concrete	Cast in situ: generally in stages (monolithic) Precast: structural units are erected and connected either mechanically or chemically Cantilever technique Segmental technique: polylithic structures Lift slab technique Tilt-up technique	A Force field applied to structural unit ↓ Torsion B Force field applied to structural unit (consisting of an assembly of components) ↓ Torsion in component units C Force field applied to structural unit (consisting of an assembly of components) ↓ No Torsion in component units	Axial, Shear, Flexure } and comb. Torsion + Axial Torsion + Flexure Torsion + Axial + Flexure Torsion + Flexure + Shear Torsion + Axial + Flexure + Shear NOTE: CHECK STABILITY OF STRUCTURE AS REQUIRED	Axial, Shear, Flexure, Torsion } and comb.	Axial, Shear, Flexure, Torsion } and comb.
1	2	3	4	5	6	7

Fig. 1-5 — General synthesis of relevant relationships to be considered in evaluating torsional effects