

Guide for the Design and Construction of Fixed Offshore Concrete Structures

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The report provides a guide for the design and construction of fixed reinforced and/or prestressed concrete structures for service in a marine environment. Only fixed structures which are founded on the seabed and obtain their stability from the vertical forces of gravity are covered.

Contents include: materials and durability; dead, deformation, live, environmental, and accidental loads; design and analysis; foundations; construction and installation; and inspection and repair. Two appendixes discuss environmental loads such as wave, wind, and ice loads in detail, and the design of offshore concrete structures for earthquake resistance.

Keywords: anchorage (structural); concrete construction; construction materials; cracking (fracturing); dynamic loads; earthquakes; earthquake resistant structures; foundations; grouting; harbor structures; inspection; loads (forces); ocean bottom; offshore structures; post-tensioning; prestressed concrete; prestressing steels; reinforced concrete; repairs; static loads; structural analysis; structural design; underwater construction.

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PREFACE

Concrete structures have been used in the North Sea and other offshore areas of the world. With the rapid expansion of knowledge of the behavior of concrete structures in the sea, and discoveries of hydrocarbons off North American shores, there will likely be an increased use of such structures. This report was developed to provide a guide for the design and construction of fixed offshore concrete structures. Reference to the following documents is acknowledged:

API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms, API RP2A, American Petroleum Institute.

Recommendations for the Design and Construction of Concrete Sea Structures, Fédération International de la Précontrainte.

Rules for the Design, Construction, and Inspection of Offshore Structures, Det Norske Veritas.

Where adequate data were available, specific recommendations were made, while in less developed areas particular points were indicated for consideration by the designer. The design of offshore structures requires much creativity of the designer, and it is intended that this guide permit and encourage creativity and usage of continuing research advancements in the development of structures that are safe, serviceable and economical.

NOTATION

- A = accidental load
 C_m = hydrodynamic coefficient
 D = dead load, diameter of structural member
 E = environmental load
 E_c = concrete modulus of elasticity
 E_i = initial modulus of elasticity
 E_o = frequently occurring environmental load
 E_{max} = extreme environmental load
 E_s = reinforcing steel modulus of elasticity
 L = live load
 L_{max} = maximum live load
 L_{min} = minimum live load
 T = deformation load
 W/C = water-cement ratio
 b = section width
 d_b = diameter of reinforcing bar
 d_e = effective tension zone
 f_c = stress in concrete
 f_{CD} = allowable design stress in concrete
 f_s = stress in reinforcing bar
 f_{SD} = allowable design stress in reinforcing bar
 f_t = mean tensile strength of concrete
 f_y = yield stress of reinforcing bars
 f'_c = 28-day strength of concrete (ACI 318)
 h = section thickness
 x = depth of compression zone
 γ_c = material factor for cohesive soils
 γ_f = material factor for friction type soils
 γ_L = load multiplier
 γ_m = material factor
 γ_{mc} = material factor for concrete
 γ_{ms} = material factor for reinforcing bars
 Δ_{ps} = increase in tensile stress in prestressing steel with reference to the stress at zero strain in the concrete
 ϵ = strain
 λ = wave length
 ϕ = strength reduction factor

CHAPTER 1-GENERAL

1.1-Scope

This report is intended to be used as a guide for the design of fixed reinforced and/or prestressed concrete structures for service in a marine environment. Only fixed structures which are founded on the seabed and obtain their stability from the vertical forces of gravity are covered herein. Such structures may be floated utilizing their own positive buoyancy during construction and installation, however.

This report is not intended to cover maritime structures such as jetties or breakwaters, or those which are constructed primarily as ships or boats. ACI 318 should be used together with this report. Because of the nature of the marine environment, certain recommendations herein override the requirements of ACI 318.

1.2-Instrumentation

In regions of the structure or foundation where it is neces-



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sary to actively control conditions to insure an adequate margin of safety for the structure, instrumentation should be provided to monitor the conditions. Such conditions might be fluid level, temperature, soil pore water pressure, etc.

Adequate instrumentation should be provided to insure proper installation of the structure.

When new concepts and procedures that extend the frontier of engineering knowledge are used, instrumentation should be provided to enable measured behavior to be compared with predicted behavior.

1.3-Auxiliary systems and interfaces

Special consideration should be given to planning and designing auxiliary nonstructural systems and their interfaces with a concrete structure.

Auxiliary mechanical, electrical, hydraulic, and control systems have functional requirements that may have a significant impact on structural design. Special auxiliary systems may be required for different design phases of an installation, including construction, transportation, installation, operation, and relocation.

Unique operating characteristics of auxiliary systems should be considered in assessing structural load conditions. Suitable provisions should be made for embedments and penetrations to accommodate auxiliary equipment.

CHAPTER 2-MATERIALS AND DURABILITY

2.1-General

All materials to be used in the construction of offshore concrete structures should have documentation demonstrating previous satisfactory performance under similar site conditions or have sufficient backup test data.

2.2-Testing

2.2.1- Tests of concrete and other materials should be performed in accordance with applicable standards of ASTM listed in the section of ACI 318 on standards cited. Complete records of these tests should be available for inspection during construction and should be preserved by the owner during the life of the structure.

2.2.2- Testing in addition to that normally carried out for concrete Structures, such as splitting or flexural tensile tests, may be necessary to determine compliance with specified durability and quality specifications.

2.3-Quality control

2.3.1- Quality control during construction of the concrete structure is normally the responsibility of the contractor. Supervision of quality control should be the responsibility of an experienced engineer who should report directly to top management of the construction firm. The owner may provide quality assurance verification independent of the construction firm.

2.4-Durability

2.4.1- Proper ingredients, mix proportioning, construction procedures, and quality control should produce durable concrete. Hard, dense aggregates combined with a low water-cement ratio and moist curing have produced concrete structures which have remained in satisfactory condition for 40 years or more in a marine environment.

2.4.2- The three zones of exposure to be considered on an offshore structure are:

(a) The submerged zone, which can be assumed to be continuously covered by the sea water.

(b) The splash zone, the area subject to continuous wetting and drying.

(c) The atmospheric zone, the portion of the structure above the splash zone.

2.4.3- Items to be considered in the three zones are:

(a) Submerged zone-Chemical deterioration of the concrete, corrosion of the reinforcement and hardware, and abrasion of the concrete.

(b) Splash zone-Freeze-thaw durability, corrosion of the reinforcement and hardware and the chemical deterioration of the concrete, and abrasion due to ice.

(c) Atmospheric zone-Freeze-thaw durability, corrosion of reinforcement and hardware, and fire hazards.

2.5-Cement

2.5.1- Cement should conform to Type I, II, or III portland cements in accordance with ASTM C 150 and blended hydraulic cements which meet the requirements of ASTM C 595.

2.5.2- The tricalcium aluminate content (C_3A) should not be less than 4 percent to provide protection for the reinforcement. Based on past experience, the maximum tricalcium aluminate content should generally be 10 percent to obtain concrete that is resistant to sulfate attack. The above limits apply to all exposure zones.

2.5.3- Where oil storage is expected, a reduction in the amount of tricalcium aluminate (C_3A) in the cement may be necessary if the oil contains soluble sulfates. If soluble sulfides are present in the oil, coatings or high cement contents should be considered.

2.5.4- Pozzolans conforming to ASTM C 618 may be used provided that tests are made using actual job materials to ascertain the relative advantages and disadvantages of the proposed mix with special consideration given to sulfate resistance, workability of the mix, and corrosion protection provided to the reinforcement.

2.6-Mixing water

2.6.1- Water used in mixing concrete should be clean and free from oils, acids, alkalis, salts, organic materials, or other substances that may be deleterious to concrete or reinforcement. Mixing water should not contain excessive amounts of chloride ion. (See [Section 2.8.6](#)).

2.7-Aggregates

2.7.1- Aggregates should conform to the requirements of ASTM C 33 or ASTM C 330 wherever applicable.

2.7.2- Marine aggregates may be used when conforming to ASTM C 33 provided that they have been washed by fresh water so that the total chloride and sulfate content of the concrete mix does not exceed the limits defined in Section 2.8.6.

2.8-Concrete

2.8.1- Recommended water-cement ratios and minimum 28-day compressive strengths of concrete for the three exposure zones are given in Table 2.1.

2.8.2- Measures to minimize cracking in thin sections and to prevent excessive thermal stresses in mass concrete are necessary if more than 700 pounds of cement per cubic yard of concrete are used (415 kg per cubic meter). A minimum cement content of 600 pounds per cubic yard (356 kg per cubic meter) is recommended to obtain high quality paste adjacent to the reinforcement for corrosion protection.

2.8.3- The rise of temperature in concrete because of cement heat of hydration requires strict control to prevent steep temperature stress gradients and possible thermal cracking of the concrete on subsequent cooling. Reducing the temperature rise may be difficult in the rich mixes and thick sections required in concrete sea structures.

The control of concrete temperatures includes selection of cements which have low heat of hydration, reduced rates of placement, precooling of aggregates, the use of ice to replace some or all of the mixing water and liquid nitrogen cooling, as described in ACI 207.4R. Pozzolans may be used to replace a portion of the cement to lower the heat of hydration.

2.8.4- When freeze-thaw durability is required, the concrete should contain entrained air as recommended by Table 1.4.3 of ACI 201.2R. Air entrainment is the most effective means of providing freeze-thaw resistance to the cement paste. Conventional guidelines, such as those contained in Table 1.4.3 generally apply to unsaturated concrete. Where concrete is exposed to frost action in a marine environment, care must be taken to insure that critical water absorption does not occur. Using a rich, air-entrained mix of low water-cement ratio, a pozzolan and an extended curing period are the most effective means of producing a concrete of low permeability, which is essential in such an environment. Lightweight aggregates behave differently from normal weight aggregates. The pores in lightweight aggregate particles are large and less likely to fill by capillary action than normal weight aggregates. However, care must be taken to prevent excessive moisture absorption in lightweight aggregates prior to mixing. Such absorption can result in critical saturation levels if sufficient curing and drying do not take place before the structure is subjected to severe exposures. High strength lightweight aggregates with sealed surfaces are effective in limiting water absorption.

2.8.5- Where severe surface degradation of the concrete is expected to occur, the minimum specified concrete strength should be 6000 psi (42 MPa). Additional protection can be achieved by using concrete aggregates having equal or higher hardness than the abrading material or by the provision of suitable coatings or surface treatments.

2.8.6- No chlorides should intentionally be added. Total water soluble chloride ion (Cl^-) content of the concrete prior to exposure should not exceed 0.10 percent by weight of the cement for normal reinforced concrete and 0.06 percent by

weight of cement for prestressed concrete. A chloride ion (Cl^-) content of up to 0.15 percent may be acceptable in reinforced concrete but should only be used after evaluation of the potential for corrosion of the specific structure under the given environmental conditions.

2.8.7- Structural lightweight concrete should conform to ACI 213R. Where it will be exposed to a freeze-thaw environment, it should be air entrained, and additional measures contained in Section 2.8.4 should be followed.

TABLE 2.1--WATER-CEMENT RATIOS
AND COMPRESSIVE STRENGTHS FOR
THREE EXPOSURE ZONES

Zone	Maximum W/C ratio	Minimum 28-day cylinder compressive strength
Submerged	0.45	5000 psi (35 MPa)
Splash	0.40	5000 psi (35 MPa)
Atmospheric	0.40	5000 psi (35 MPa)

2.9-Admixtures

2.9.1- Admixtures should conform to Section 3.6 of ACI 318. Limits given in this section for calcium chloride should not increase the total limits recommended for concrete as outlined in Section 2.8.6 of this report. When two or more admixtures are used, their compatibility should be documented.

2.10-Reinforcing and prestressing steel

2.10.1- Reinforcing and prestressing steel should conform to Section 3.5 of ACI 318. Low temperature or cold climate applications may require the use of special reinforcing and prestressing steel and assemblages to achieve adequate ductility. To facilitate future repairs that might be necessary, only weldable reinforcement should be used in the splash zone and other areas susceptible to physical damage. Weldable reinforcement should conform to the chemical composition of ASTM A706.

2.11-Post-tensioning ducts

2.11.1- Post-tensioning ducts should conform to Section 18.15 of ACI 318.

2.11.2- Post-tensioning ducts should be semi-rigid and watertight and have at least 1 mm of wall thickness. Ferrous metal ducts or galvanized metal ducts passivated by a chromate wash may be used. Plastic ducts are not recommended.

2.11.3- Bends in ducts should be preformed as necessary. Joints in ducts should be bell and spigot with the ends cut by sawing so as to be free from burrs and dents.

Joint sleeves should fit snugly and be taped with waterproofing tape. Splices should preferably be staggered but where this is impracticable, adequate space should be provided to insure that the concrete can be consolidated around each splice.

2.11.4- If flexible metal ducts must be used in special areas of congestion, etc., they should have a mandrel inserted during concrete placement. Bars for supporting and holding down such ducts should have a curved bearing plate against the duct to prevent local crushing.

2.12-Grout

2.12.1- Grout for bonded tendons should conform to Section 18.16 of ACI 318 and to applicable sections of this report. Suitable procedures and/or admixtures should be used to prevent pockets caused by bleeding when grouting of vertical tendons or tendons with substantial vertical components.

2.12.2- Recommendations for mixing water outlined in Section 2.6 also apply to grout mixes.

2.12.3- Admixtures may be used only after sufficient testing to indicate their use would be beneficial and that they are essentially free of chlorides, or any other material which has been shown to be detrimental to the steel or grout.

2.13-Concrete cover of reinforcement

2.13.1- Recommended nominal concrete covers for reinforcement in heavy concrete walls, 20 in. (50 cm) thick or greater are shown in Table 2.2.

Concrete covers of reinforcement should not be significantly greater than prescribed minimums to restrict the width of possible cracks. This would be more critical for those members in flexure.

Table 2.2-RECOMMENDED NOMINAL
CONCRETE COVER OVER REINFORCEMENT

Zone	Cover over reinforcing steel	Cover over post-tensioning ducts
Atmospheric zone not subject to salt spray	2 in. (50 mm)	3 in. (75 mm)
Splash and atmospheric zone subject to salt spray	2.5 in. (65 mm)	3.5 in. (90 mm)
Submerged	2 in. (50 mm)	3 in. (75 mm)
Cover of stirrups	½ in. (13 mm) less than those listed above	

2.13.2- If possible, structures with sections less than 20 in. (50 cm) thick should have covers as recommended in Section 2.13.1, but when clearances are restricted the following may be used with caution. Cover shall be determined by the maximum requirement listed below:

- (a) 1.5 times the nominal maximum size of aggregate, or
- (b) 1.5 times the maximum diameter of reinforcement, or
- (c) ¾ in. (20 mm) cover to all steel including stirrups.

Note: Tendons and post-tensioning ducts should have 0.5 in. (13 mm) added to the above.

2.14-Details of reinforcement

2.14.1- Reinforcement details should conform to Chapters 7 and 12 of ACI 318.

2.14.2- Special consideration should be given to the detailing of splices used in areas subjected to significant cyclic loading. Staggered mechanical and welded splices should preferably be used in these instances. Lap splices, if used, should conform to the provisions of ACI 318. In general, noncontact lap splices should be avoided unless adequate justification can be developed for their use. Mechanical devices

for positive connections should comply with the section of ACI 318 dealing with mechanical connections. Welded splices may be used where reinforcing steel meets the chemical requirements of ASTM A706.

2.14.3- Mechanical or welded connections should be used for load-carrying reinforcing bar splices located in regions of multiaxial tension, or uniaxial tension that is normal to the bar splices.

2.15-Physical and chemical damage

2.15.1- In those areas of the structure exposed to possible collision with ships, flotsam, or ice, additional steel reinforcement should be used for cracking control and concrete confinement. Particular consideration should be given to the use of additional tension reinforcement on both faces and additional shear reinforcement (transverse to walls) to reinforce for punching shear. Unstressed tendons and unbonded tendons are two techniques which can be used to increase the energy absorption of the section in the post-elastic stage.

2.15.2- The possibility of materials and equipment being dropped during handling on and off the platform should be considered. Impact resisting capacity may be provided as mentioned in Section 2.15.1. In addition, protective coverings may be installed such as steel or concrete grids and energy-absorbing materials such as lightweight concrete.

2.15.3- A polymer or other special coating may be used to control ice abrasion or adfreeze between an ice feature and a structure. Compatibility between a coating and the underlying concrete should be assessed to preclude problems with bond development, coating delamination caused by air or moisture migration, and freeze-thaw effects.

2.15.4- Exposed steel work and its anchor systems should be electrically isolated from the primary steel reinforcement by at least 2 in. (50 mm) of concrete. The use of cathodic protection systems is generally not required for reinforcing steel and prestressing steel embedded in concrete.

2.15.5- Exposed steel work should normally be painted or coated to reduce corrosion. Particular care should be taken to insure against corrosion on the edges and horizontal surfaces. Epoxy coatings are normally used for protection of carbon steel plates and fittings. Cathodic protection systems for externally exposed steel should be of the sacrificial anode type. Impressed current should not be used unless positive controls are instituted to prevent embrittlement of the reinforcing and prestressing steel.

2.16-Protection of prestressed anchorages

2.16.1- The anchorages of prestressed tendons should be protected from direct contact with seawater, which could lead to corrosion. A desirable method is to use recessed pockets so that the steel anchorage and tendon ends may be protected by concrete or grout fill in the pocket. The pocket surface should be thoroughly cleaned and the exposed steel should be coated with bonding epoxy just prior to placing the concrete or grout fill. Particular care should be taken to prevent shrinkage and the formation of bleed lenses. Alternative details are acceptable provided they are designed to limit the penetration of seawater and oxygen to the same degree as that provided to the tendon proper.

2.17-Anchorage for embedments and connections to steel work

2.17.1- Embedments may be anchored by studs, steel bars, or prestressing tendons. Welds should conform to AWS D1.1 or AWS D1.4.

2.17.2- Prestressing tendons should normally be used to provide precompression in regions where connections or embedments are subject to cyclic or high dynamic loads.

2.17.3- The concrete section to which the embedment or connection is anchored should be adequately reinforced to prevent pullout shear and delamination.

2.17.4- Steel plates should have adequate properties to insure against delamination.

2.17.5- Where welding will subsequently be carried out on the embedment plate, the effect of heat must be considered. A wood or rubber chamfer strip may be placed around the plate while the concrete is formed to create a reveal and thus prevent spalling of the adjacent concrete. Where long-term protection of vital embedments must be assured, epoxy may be injected behind the plate which has been subjected to heat distortion.

2.18-Electrical ground

2.18.1- An electrical ground conductor should be provided to protect prestressing tendons and reinforcing steel from accidentally acting as a ground for lightning discharges and other sources of electrical current.

2.19-Durability of pipes containing pressure

2.19.1- Where long term operation of the platform requires continual pressure difference between the surrounding sea and contained fluids, pipes critical to the maintenance of this pressure and virtually inaccessible should be designed with excess corrosion resistance. Flanged connections and inaccessible valves should be avoided.

2.20-Epoxy resins

2.20.1- Epoxy resins may be used for waterproofing coatings, sealing construction joints, repairing cracks, and other similar usages. The epoxy resins should be carefully selected on the basis of the materials' suitability for the particular application. Required strength, ability to cure and bond to wet concrete for the temperatures involved should all be considered. Refer to ACI Committee 503 recommendations and to manufacturers' instructions, along with specialist literature.

CHAPTER 3-LOADS

3.1- Classifications

Loads may be classified as follows:

Dead loads *D*

Deformation loads *T*

Live loads *L*

Environmental loads *E*

Accidental loads *A*

3.1.1 Dead loads- Dead loads are permanent static loads such as:

Weight of the structure

Permanent ballast and equipment that cannot be removed

External hydrostatic pressure

3.1.2 Deformation loads- Deformation loads consider the effects of the following:

Temperature, including heat of hydration

Differential settlements and uneven seabed

Creep and shrinkage

Initial strains imposed by prestressing cables

3.1.3 Live loads- Live loads may be static or dynamic and may vary in position and magnitude.

Live loads may also result from operation of the structure.

The following are representative examples:

Helicopters

Loads induced by the operation of equipment

Liquids stored internally

Equipment and supplies

Berthing, breasting, and mooring loads

Snow and accumulated ice

3.1.4 Environmental loads- Environmental loads are due to natural phenomena and may result from the following (see Appendix A):

Waves

Wind

Current

Earthquake

Ice (sheet ice, first-year and multiyear ridges, icebergs, etc.)

Marine growth

3.1.5 Accidental loads- Accidental loads result from accidents or misuse, such as:

Collision from service boats, barges, and ships

Dropped objects

Explosion

Loss of assumed pressure differential

3.2-Design phases

Loads listed above should be considered for each design phase, including:

Construction

Transportation

Installation

Operation

Retrieval

CHAPTER 4-DESIGN AND ANALYSIS

4.1-General

In addition to the strength and serviceability requirements described below, the survivability of the structure should also be investigated to insure that the structure-foundation system will endure extreme environmental events without catastrophic failure. Appendix B includes survivability criteria for earthquake design of concrete structures.

The guidelines in this section are intended to provide a readily applied basis for practical analysis and design. However, nothing herein is intended to prevent the use of more detailed analytical methods.

Insofar as practicable, the designer should select structur-

TABLE 4.1-ALLOWABLE TENSILE STRESSES FOR PRESTRESS AND REINFORCING STEEL TO CONTROL CRACKING

Stage	Loading	Allowable stress, ksi	
		Δ_{ps}	f_s
Construction: Where cracking during construction would be detrimental to the completed structure	All loads on the structure during construction	18.5 (130 MPa)	23.0 (160 MPa)
Construction: Where cracking during construction is not detrimental to the completed structure	All loads on the structure during construction	18.5 (130 MPa)	30 (210 MPa) or $0.6f_y$, whichever is less
Construction	All loads on the structure during transportation and installation	18.5 (130 MPa)	23.0 (160 MPa)
At offshore site	Dead and live loads plus monthly recurring environmental loads	11.0 (75 MPa)	17.0 (120 MPa)
At offshore site	Dead and live loads plus extreme environmental loads		$0.8f_y$

al configurations and reinforcing details that will insure a ductile (nonbrittle) mode of failure and avoid progressive collapse.

4.2-Strength

The strength of the structure should be such that adequate safety exists against failure of the structure or its components. Among the modes of possible failure that should be considered are:

1. Loss of overall equilibrium
2. Failure of critical sections
3. Instability resulting from large deformations
4. Excessive plastic or creep deformation

4.3-Serviceability

The structure should be capable of operating according to its intended function under extreme imposed loading and frequently occurring environmental conditions. Among the conditions that could cause the structure to become unserviceable are:

1. Excessive cracking
2. Unacceptable deformations
3. Corrosion of reinforcement or deterioration of concrete
4. Undesirable vibrations
5. Excessive leakage

4.4-Design conditions

4.4.1 Strength requirements-A structure should have adequate strength to resist extreme forces resulting from environment or man-made causes without sustaining permanent damage. It is assumed that these forces will occur at least once during the expected service life of a structure.

Extreme environmental and man-made conditions requiring strength design considerations are either of the following:

(a) Surface waves, currents, and winds with long period recurrence intervals (see [Appendix A](#))

(b) Severe earthquake ground motions (see [Appendix B](#) for design earthquakes)

(c) Temporary submergence during construction and deck installation and installation of the structure on site

(d) Severe ice conditions

The recommended recurrence interval for all environmental events is generally 100 years, except that for temporary exposures such as during construction and towing the recurrence interval of the extreme environmental event may be reduced to be commensurate with the actual exposure period and season in which the operation takes place.

4.4.1.1 Load combinations. The required strength of the structure and each member should be equal to or greater than the maximum calculated by the following:

$$U = 1.2(D + T) + 1.6L_{max} + 1.3E_o \quad (4-1)$$

$$U = 1.2(D + T) + 1.2L_{max} + \gamma_L E_{max} \quad (4-2)$$

$$U = 0.9(D + T) + 0.9L_{min} + \gamma_L E_{max} \quad (4-3)$$

L_{max} = maximum live load

L_{min} = minimum live load

E_o = frequently occurring environmental load (e.g., monthly)

E_{max} = Extreme environmental load

γ_L = load multiplier and assumes following values: waves plus current plus wind, $\gamma_L = 1.3$, earthquakes (see [Appendix B](#)), ice, $\gamma_L =$ (should be selected to be consistent with the method of analysis used to calculate the design ice load and should reflect the quality of the data available to describe the design ice feature).

For dead loads D , the load multiplier should be replaced by 1.0 if it leads to a more unfavorable load combination. In Eq. (4-1) the multiplier 1.3 on E_o should be reduced if a more unfavorable load combination results.