7 Structural Strengthening

Table of Contents

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7.1 Introduction

Strengthening or increase in ductility of bridge members may be required for a variety of reasons including increasing capacity for vehicle loads and improving earthquake resistance.

This chapter sets out criteria for the design of strengthening for concrete or steel bridge members for the following situations, materials and techniques:

- the strengthening of members using bonded steel plates or fibre reinforced polymer composite materials;
- the strengthening of members using external prestressing;
- the shear strengthening and ductility enhancement of reinforced concrete columns using steel sleeves or fibre reinforced polymer composite materials.

7.2 Approvals

Technologies for the strengthening of structures are continually under development. This chapter provides design criteria and guidance based on published information available at the time of preparation.

Where a bridge is to be strengthened, a Design Statement, as set out in Section 1 of this manual, shall be prepared and submitted for Transit New Zealand approval. The materials and procedures for the proposed strengthening shall be fully described, including the criteria forming the basis of the design. The following shall be included:

- the mode of failure at the ultimate limit state, and measures to be taken to ensure that other modes of failure are precluded;
- the strength reduction factors to be adopted for the various modes of action;
- design standards and reference papers setting out and / or supporting the design criteria and design approach proposed;
- durability issues, and proposed mitigation measures;
- intended remaining life of the structure and design life of the strengthening system.

7.3 Durability

7.3.1 General

The requirements of 2.1.7 of this manual shall be satisfied. Design life in this context shall be taken to be the intended remaining life of the strengthened structure.

Consideration shall be given to the vulnerability of the strengthening system to harmful hazards associated with the operational environment, including, but not limited to: exposure to water (marine, fresh, or from industrial sources, and including the effects of wetting and drying), the effects of ground water and soil chemistry, the passage of water and abrasion from material transported, abrasion by traffic, cycles of temperature variation, freeze-thaw cycles, heat or cold associated with the construction, maintenance or operation of the structure, fatigue, stress corrosion, strain aging, galvanic corrosion, exposure to fire, exposure to lightening and stray electric currents, acts of vandalism, accidental impact, and chemical spillage. Appropriate mitigation measures shall be implemented.

7.3.2 Fibre Reinforced Polymer Composites and Adhesives

In addition to the requirements of 7.3.1, consideration shall be given to the effects of exposure to the following, as appropriate:

- ultra violet light
- contact with alkaline materials
- creep
- stress rupture

7.4 Existing Structure Material Strengths

Where the characteristic strengths of the existing concrete and reinforcement or structural steel are not known they shall be determined from testing as set out in 6.3. The characteristic strength of prestressing steel shall be determined as set out in 6.3.3.

7.5 Strengthening of Flexural Members

7.5.1 General Requirements for the Strengthening of Reinforced Concrete and Prestressed Concrete Members

Strengthening shall, where appropriate, comply with, and be consistent with the requirements of the NZS 3101, Concrete Structures Standard[(1)].

Strength reduction factors used for assessment of the reliable strength at the ultimate limit state shall not exceed those given by NZS 3101[(1)] Cl. 3.4.2.2.

7.5.2 General Requirements for the Strengthening of Steel Members

Strengthening shall, where appropriate, comply with, and not be inconsistent with the requirements of the relevant standard for structural steel design as set out in 4.3.1.

Strength reduction factors or partial safety factors used for the assessment of reliable strength at the ultimate limit state shall not exceed those given by the relevant structural steel standard set out in 4.3.1.

7.5.3 Flexural Strengthening of Plastic Hinge Zones

Bonded steel plates, providing flexural strengthening at member sections at which plastic hinging is likely to occur under response to a design intensity earthquake event, shall be fully anchored outside the zone of plastic hinging. The bonded steel plates shall be fully confined over their length against buckling in accordance with the principles on which NZS 3101[1] requirements for confining reinforcement are based.

Flexural strengthening using fibre reinforced polymer composites as primary flexural reinforcement, or using prestressing to increase the axial load on the section, shall not be applied at member sections at which plastic hinging is likely to occur under response to a design intensity earthquake event.

7.5.4 Strengthening Using Bonded Steel Plates

(a) General and Design Principles

Design for the strengthening shall be undertaken at the serviceability limit state, based on the principles of elastic superposition and strain compatibility, and also at the ultimate limit state to ensure adequacy of strength and factor of safety against failure, with consideration to the mode of failure. The adequacy of the strengthened member for shear shall be confirmed.

The United Kingdom Department of Transport Advice Note BA 30/94, *Strengthening of Concrete Highway Structures Using Externally Bonded Plates*[2], provides guidance on design for strengthening using bonded steel plates and may be adopted subject to the modifications noted herein.

(b) Applicability of Strengthening using Bonded Steel Plates

In the event of unexpected failure of the strengthening system, the structure shall remain capable of supporting its permanent loads plus nominal live load. A member shall only be considered suitable for strengthening by plate bonding if it can be shown to be at least capable of supporting 1.20 (DL + EP + OW + SG + ST) + LLxI + FP when checked at the ultimate limit state. (Refer to 3.5 for definitions of the individual loadings).

(This amends BA 30/94 Cl. 2.1).

Bonded steel plates shall not normally be used to provide resistance for significant permanent loads on the structure.

(c) Strength Reduction Factors

Strength reduction factors for section design at the ultimate limit state shall not exceed those given in NZS 3101[1] Cl. 3.4.2.2 or the relevant standard for structural steel design as appropriate. Where the structure is deteriorated, the design strength reduction factors shall be modified as set out in Table 6.5. The strength reduction factor, ϕ, shall not exceed 0.75 for the following aspects of design:

(i) plate peeling

(ii) plate development

The strength reduction factors adopted shall ensure that a flexural mode of failure (i.e. by plate yielding or concrete crushing) precedes failure by plate peeling or bond failure.

(This amends BA 30/94 Cl. 3.2).

(d) Brittle Failure

The over-reinforcement of a concrete section can result in brittle failure. Sections to be strengthened should therefore be checked to ensure that this does not occur. NZS 3101[(1)] Cl. 8.4.2 shall be complied with.

(This amends BA 30/94 Cl. 3.3).

(e) Fatigue

Fatigue of the bonded steel plate, the bonding material, and the reinforcement or structural steel section of the original member, under frequently repetitive imposed loads and forces on the structure shall be considered. For concrete members, NZS 3101[(1)] Cl. 3.7.2 shall be complied with. Cl. 3.7.2.2 shall also apply to the stress range within the bonded steel plates. For steel members, the requirements of the relevant standard for structural steel design shall be complied with.

(This amends BA 30/94 Cl. 3.5).

Where the strengthening is applied to the top surface of a bridge deck, consideration shall also be given to the fatigue effect from individual vehicle wheels applying normal and traction forces to the strengthening.

(f) Yielding of Original Member Reinforcement or Section

The manner of strengthening shall be such that the reinforcement of an original concrete member, or part of the section of an original steel member, shall not be subjected to yielding under service loads to be imposed on the strengthened member.

(g) Plate Peeling

The phenomenon of premature failure of the bonded steel plates by plate peeling shall be taken into account and guarded against. The following principles are relevant:

(i) When a beam is subjected to a load perpendicular to its length, reactions are developed at its supports and the beam takes up a deflected shape. If strengthening in the form of bonded plates are added to the beam, to enable it to resist the load, then the plates must also take up a compatible deflected shape to that of the beam. This is brought about through the mobilisation of normal forces acting across the interface between the beam and the bonded plate, compressive towards the centre of the span, and tensile in the end regions of the plate.

(ii) For the bonded plate to act as composite strengthening, it must take up strain such that as the beam deflects, plane sections remain plane, developing longitudinal shear stresses on the interface between the plate, adhesive and the face of the beam to achieve strain compatibility.

Fixings shall be used to develop the normal forces and longitudinal shear stresses involved. In reinforced concrete members, tension in the cover concrete shall not be relied on for these actions. Where BA 30/94(2) Cl. 3.7 is adopted as the basis for the design of fixings, the requirements of BA 30/94(2) Cl. 3.4 shall also be satisfied. Fixings detailed in accordance with BA 30/94(2) Cl. 3.7 shall be confirmed to provided adequate fixing for the normal forces in addition to the longitudinal shear forces, and shall also be detailed and confirmed to satisfy the other requirements of this clause, including (h) below.

In addition, the effect of yielding of the reinforcement in the original concrete member, or of the original section of a steel member, at the ultimate limit state, on the level and distribution of bond stress along the member shall be taken into account and provided for. (*Retrofit of Reinforced Concrete Members using Advanced Composite Materials*(3) provides a presentation of this effect in respect to reinforced concrete members.)

(h) Truss Analogy for Reinforced Concrete Members

The mode of behaviour of a reinforced concrete beam can be considered to be analogous to a truss. When plate reinforcement is added to the soffit face of a reinforced concrete beam it lies outside the beam shear reinforcement, and in effect, the “truss” web. A mechanism, other than tension in the cover concrete, shall be provided to incorporate that plate into the “truss” action of the concrete beam.

Approaches that may be used to incorporate the plate into the “truss” action of the concrete beam, effectively by extending the “truss” web down to the level of the strengthening plate, include:

- bolting, lapped a development length with the beam shear reinforcement;
- plates bonded to the side faces of the beam and attached to the flexural strengthening soffit plate, lapped a development length with the beam shear reinforcement; or
- fibre reinforced polymer strips wrapped around the flexural strengthening soffit plate and bonded up the side faces of the beam, lapped a development length with the beam shear reinforcement.

Where plates or fibre reinforced polymer strips bonded up the side faces of the beam are used to incorporate the soffit plate into the beam’s “truss” action, the top ends of these plates or strips shall be mechanically fixed to prevent them from also peeling. On wide beams, a combination of side plates / strips and bolting may be necessary to prevent the soffit plate cross-section from bowing and to adequately incorporate the soffit plate into the beam’s “truss” action.

(i) Effect of Loading During Curing on Adhesive Strength

Where the structure is subjected to live loading or other environmental loadings during curing of the adhesive, following installation of the steel plates, the effect of such loading on the final strength of the adhesive shall be taken into account.

(j) Irregularity of the Surface to Which Plates are to be Bonded

The effect of irregularity of the bonding surface on the strengthening shall be taken into account, including the effects arising from deviation of the strengthening plate from perfect alignment (giving rise to a tendency for the plate to initially straighten when taking up load). The effect on the bond stresses from the strengthening plate not being perfectly aligned shall also be taken into account.

(k) Materials

Materials shall comply with BA 30/94(2) Section 4.

(l) Surface Preparation and Corrosion Protection

Surface preparation of the concrete and steel surfaces shall comply with BA 30/94(2) Section 5.

Interface steel surfaces may be protected against corrosion using a primer that is compatible with the initial bond primer and adhesive. Where a corrosion protection system is used, its effect on the bond strength of the interface shall be taken into account.

7.5.5 Strengthening Using Bonded Fibre Reinforced Composite Materials

(a) General

Fibre reinforced polymer composite materials encompass a wide range of materials, manufactured by a number of different processes. The most commonly used fibre and resin materials, used to make up the composite materials covered by this clause, include the following:

- Fibre types: carbon, aramid, glass, and polyethylene;
- Resins: epoxy and vinyl ester.

Strengthening using bonded fibre reinforced polymer composites shall be in accordance with the same principles and requirements as set out in 7.5.4 for strengthening using bonded steel plates, except as modified below.

Retrofit of Reinforced Concrete Members Using Advanced Composite Materials(3) provides useful guidance on flexural and shear strengthening using fibre reinforced polymer composite materials, but note that 7.5.4 (a) first paragraph and 7.5.4 (b) shall apply.

(b) Track Record, Manufacturing Processes and Quality Control

The fibre reinforced polymer composite material to be used shall have a track record of use in service that has demonstrated adequate durability, or alternatively the durability of the material shall be substantiated by test data.

The material shall be of adequate quality. This requires the choice of appropriate fibres and resins, combined in an appropriate manufacturing process with the necessary quality controls. The strength properties adopted for design shall be statistically based and have a confidence limit of not less than 95%, (i.e. not more than 5% of the test results will fall below the adopted design properties). The elastic modulus assumed for design shall be the mean value.

(As a guide to quality, references (4) and (5) present tables of typical fibre properties for the different types of fibre reinforced polymers. Fibres of a fibre-reinforced polymer would be expected to conform to these typical properties. Some differences exist between the tables contained in the two references.)

(c) Material Characteristics, Mode of Failure, and Strength Reduction Factors

In general, fibre reinforced polymer composite materials behave in a linearly elastic manner up to failure. They also, generally, have a significantly lower strength in compression than in tension. Externally bonded laminates or sheets are generally unsuitable for use in compression due to the impracticality of providing sufficient restraint against buckling.

The elastic modulii of fibre reinforced polymer composite materials vary widely dependent on the particular fibre type and on the mode of manufacture of the fibre reinforced polymer material. The elastic modulus of the particular composite material to be used for the strengthening shall be taken into account in the design.

For a reinforced or prestressed concrete beam strengthened using a fibre reinforced polymer composite material, three modes of failure are possible:

(i) by extensive yielding of the beam’s original steel reinforcement, spalling of the compression cover concrete and moment capacity drop-off;

(ii) by rupture of the fibre reinforced polymer composite flexural strengthening material; or

(iii) by brittle failure of the concrete in the member compression zone.

Where possible, for a strengthened concrete or steel section, the desired mode of behaviour is for the flexural steel reinforcement or structural steel section to yield prior to failure of the section, providing a noticeable increase in deflection and thereby warning of imminent failure.

In the case of failure of a concrete member by rupture of the fibre reinforced polymer composite flexural strengthening, the strain in the extreme concrete fibre in compression may be < 0.003 when the ultimate tensile strain in the fibre reinforced polymer composite material is reached. As a result, the equivalent rectangular stress block adopted for concrete in the standard design procedure cannot be used.

A moment-curvature analysis, involving calculation of the neutral axis depth and strains in all the contributing materials, should be used for the analysis of the strengthened section.

Strength reduction factors appropriate to fibre reinforced polymer materials are currently undergoing development. Appropriate strength reduction factors for application at the ultimate limit state and serviceability limit state for the different modes of behaviour shall be developed from a review of current international literature from reputable sources (e.g. American Concrete Institute, UK Concrete Society, Federation International du Béton) and on the basis of sound engineering principles. The strength reduction factors proposed to be applied in the design shall be submitted to Transit for approval.

For reinforced concrete, prestressed concrete, and structural steel members, the strength reduction factors for flexural design of fibre reinforced polymer composite strengthening, at the ultimate limit state, shall be as follows:

(i) Where failure is preceded by a significant amount of ductile yielding, the strength reduction factor shall not be greater than $\phi = 0.85$.

(ii) Where the mode of failure is non-ductile, the strength reduction factor shall not be greater than $\phi = 0.75$.

The strength reduction factor, ϕ, shall not be greater than 0.75 for the following aspects of design:

(i) Laminate or sheet peeling;

(ii) Laminate or sheet development.

The strength reduction factors adopted shall ensure that a flexural mode of failure (e.g. by rupture of the fibre reinforced polymer composite material or concrete crushing) precedes failure by peeling or bond failure.

(d) Method of Analysis

Elastic analysis shall be used to analyse the structure, and no redistribution of the elastic bending moments and shear forces is permitted in view of the lack of ductility of the fibre reinforced polymer composite material.

(This amends NZS 3101 Cl. 4.3.3.3).

(e) Strengthening of Concrete Members for Shear

Concrete members strengthened for shear by using strips of fibre reinforced polymer composite material shall be designed for shear in accordance with the requirements of NZS 3101(1) Chapter 9. Under these requirements, fibre reinforced polymer composite strip reinforcement shall be treated in the same manner as steel reinforcement with the stress in the fibre reinforcement corresponding to a strain of 0.004 substituted in place of the steel yield stress. Under these conditions, the contributions to shear reinforcement of the existing steel reinforcement and of the fibre reinforced polymer composite strip reinforcement may be considered additive.

The ends of fibre reinforced polymer composite strips shall be adequately anchored to develop the design forces in the strips. In situations where a slab overlies a beam being strengthened (as with a T- beam), the preferred approach is for intermittent slots to be cut in the slab and the fibre reinforced polymer strips passed through the slab and anchored on the slab top surface. Where the strips are to be terminated below a slab, consideration shall be given to the transfer of the force in the fibre reinforced polymer strips to the “truss” mechanism of the reinforced concrete member, and to the shear that may be induced in the concrete member above the level of the ends of the strips. (Reference 3 provides guidance on this issue.) Where proprietary mechanical anchors or clamps are used to develop the design force in the strips, the performance of proprietary mechanical anchors or clamps shall have been substantiated by testing and their reliability established by statistical analysis. Anchor capacities adopted as the basis for design shall have a probability of being exceeded of not less than 95%.

Depending on the manufacturing process, the strength of fibre reinforced polymer composite material shear reinforcement may be significantly less locally at corners than within straight portions. This shall be taken into account in the design.

(f) Design Guidelines

A number of design guidelines related to bonded fibre reinforced composite materials have been published internationally. There are differences in approach between the guidelines, and it is recommended that reference be made to several guidelines and references in seeking guidance on the application of these materials. These design guidelines are references 3, 4, 5 and 6.

It should be noted that the latter three publications have been published since preparation of this section.

7.5.6 Strengthening Using External Prestressing

(a) Applicability

This clause is applicable to strengthening by externally prestressing members using conventional systems based on steel prestressing. This clause does not cover the use of fibre-reinforced polymer prestressing systems.

(b) Inspection, Maintenance and Demolition

Adequate provision shall be made for the inspection and maintenance of external tendons.

All external and unbonded tendons shall be individually replaceable without having to restrict traffic on the highway wherever possible. Where the detailing does not enable tendons to be removed and replaced without damage to either the tendons or the structure, or without restricting traffic, a method statement defining how the tendons can be replaced shall be provided in the Design Statement. A method statement defining how the structure can be demolished shall also be provided.

(c) Strengthening of Concrete Members

NZS 3101, *Concrete Structures Standard*(1), provides explicitly for the design of structures with unbonded high strength steel tendons and shall be complied with for this form of strengthening, except as modified herein.

Conventionally reinforced, non-prestressed concrete members, that are strengthened by external unbonded prestressing, shall satisfy the serviceability limit state crack width criteria for reinforced concrete set out in NZS 3101(1) Cl. 3.3.3.3. The more stringent criteria for prestressed concrete need not be complied with.

(d) Strengthening of Steel and Composite Steel - Concrete Members

7.5.2 shall apply in respect to stresses induced in the steel sections and to the design of anchorages and deviators. In the consideration of buckling of the steel section, the prestress force may be considered as an externally applied load.

For the design of the stressing tendons, the principles and requirements of NZS 3101(1) Clauses 16.3.1 to 16.3.6 should be applied as appropriate.

The strengthened members shall meet both the serviceability and ultimate limit state requirements of the relevant standard for structural steel design, and where the members include a composite concrete element, the relevant serviceability and ultimate limit state requirements of NZS 3101(1).

The strength reduction factor, ϕ, adopted for determining the reliable flexural capacity at the ultimate limit state shall be derived from the relevant standard for structural steel design.

(e) Anchorages and Deviators

Anchorages and deviators for external tendons shall be designed at the ultimate limit state for a load equal to at least the 95% of the ultimate tensile strength of the tendons with a value of $\phi = 0.85$ Where serviceability checks are required, as for flexural cracking in concrete deviator beams, the design service load in the tendons shall be taken as the tendon load before long-term losses.

The design shall ensure that bi-metallic corrosion between the tendons and their anchorages is prevented.

(f) Tendons Pretensioned Before Being Deflected

For single tendons the deflector in contact with the tendon shall produce a radius of not less than 5 times the tendon diameter for wire, or 10 times the diameter for strand. The total angle of deflection should not exceed 15°.

(g) Post-Tensioned Tendons Profile

In the absence of test results or other investigation justifying smaller values, the radius of curvature of tendons in deviators should not be less than the following minimum values:

Table 7.1: Radius of Curvature for Tendons

Tendon (Strand Number – Size)	Minimum Radius (m)
19 – 13mm and 12 – 15mm	2.5
31 – 13mm and 19 – 15mm	3.0
53 – 13mm and 37 – 15mm	5.0

(h) Tendon Restraint

External tendons shall be restrained in all necessary directions to avoid unacceptable second order effects due to beam deflections and tendon vibration.

(i) Corrosion Protection

Tendons shall be protected to ensure that their life is compatible with the life of the structure.

(j) Further Considerations to be Taken Into Account

The design takes into account the following:

- The effects of end restraint of the spans / beams being stressed, whether due to the spans being constructed integral with supports, or due to friction or elastomeric shear strain of bearings.

- The distribution of the prestress force and induced moment across all the beams making up the total cross-section, as influenced by:
- which beams are to be prestressed and by how much;
- the relative stiffness of the beam elements making up the total cross-section;
- within each span, the length over which the prestressing is to be applied and shear lag effects across the bridge deck.
- The effects of secondary moments arising from continuity of the span or from spans being constructed integral with supports.
- The effects of shortening of the spans due to the initial prestress force and long term creep.

(k) Guidance Documents

General guidance on considerations related to the design of systems for external prestressing is *provided by Materials and Systems for External Prestressing*(7).

7.6 Shear Strengthening and Ductility Enhancement of Reinforced Concrete Columns

7.6.1 General

Strengthening shall, where appropriate, comply with, or not be inconsistent with the requirements of the NZS 3101, *Concrete Structures Standard*(1).

Strength reduction factors used for the assessment of reliable strength at the ultimate limit state shall not exceed those given by NZS 3101(1) Cl. 3.4.2.2.

Extensive design guidance is provided by *Seismic Design and Retrofit of Bridges*(8) covering both strengthening using steel plate sleeves and using fibre reinforced polymer composite materials. The design approaches and recommendations contained therein may be adopted in place of the requirements of NZS 3101(1), and will generally result in a more economical design.

7.6.2 Shear Strengthening and Ductility Enhancement of Reinforced Concrete Columns Using Steel Sleeves

Concrete members strengthened for ductility or shear by using steel sleeves shall be designed in accordance with the requirements of NZS 3101(1). Alternatively, the design recommendations of *Seismic Design and Retrofit of Bridges*(8) may be adopted.

Strengthening to ensure the integrity of flexural reinforcing bar lap splices shall comply with the design recommendations of *Seismic Design and Retrofit of Bridges*(8).

7.6.3 Shear Strengthening and Ductility Enhancement of Reinforced Concrete Columns Using Fibre Reinforced Polymer Composite Materials

Concrete members strengthened for ductility or shear by using fibre reinforced polymer composite material shall be designed in accordance with the requirements of NZS 3101[(1)]. Under these requirements, fibre reinforced polymer composite strip reinforcement shall be treated in the same manner as steel reinforcement with the stress in the fibre reinforcement corresponding to a strain of 0.004 substituted in place of the steel yield stress. Under these conditions, the contributions to confinement or shear reinforcement of the existing steel reinforcement and of the fibre reinforced polymer composite strip reinforcement may be considered additive. Alternatively, the design recommendations of *Seismic Design and Retrofit of Bridges*[(8)] may be adopted.

Strengthening to ensure the integrity of flexural reinforcing bar lap splices shall comply with the design recommendations of *Seismic Design and Retrofit of Bridges*[(8)].

7.7 References

(1) NZS 3101: 1995, *Concrete Structures Standard*, Standards New Zealand.

(2) DOT (UK), 1994, BA 30/94, *Strengthening of Concrete Highway Structures Using Externally Bonded Plates*, UK Department of Transport Advice Note.

(3) Wang YC, 2000, *Retrofit of Reinforced Concrete Members Using Advanced Composite Materials*, Department of Civil Engineering Research Report 2000-3, University of Canterbury, Christchurch.

(4) The Concrete Society, 2000, *Design Guidance for Strengthening Concrete Structures using Fibre Reinforced Composite Materials*, Concrete Society Technical Report No.55, United Kingdom.

(5) FIB, 2001, *Design and Use of Externally Bonded FRP Reinforcement for Reinforced Concrete Structures*, Federation International du Béton Bulletin No.14.

(6) ACI, 2000, *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (Draft: 12 July 2000), ACI Committee 440, American Concrete Institute, United States of America.

(7) FIP, 1996, *Materials and Systems for External Prestressing*, Federation Internationale de la Preconstrainte, SETO, London.

(8) Priestly MJN, Seible F, and Calvi GM, 1996, *Seismic Design and Retrofit of Bridges*, John Wiley & Sons Inc., New York.