Design Guidelines – A Scandinavian Approach

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Agenda

- Introduction
- Background
- Strengthening in Bending
- Strengthening in Shear
- Strengthening in Torsion
- Execution
- Safety factors
- Conclusions
- Acknowledgement
Why the need for design guidelines?

- Increased need for strengthening and rehabilitation
- New materials introduced
- Knowledge how to use these materials for strengthening is relatively limited compared to traditional building materials
- To gain acceptance within the building industry
Strengthening of Structures in General

- Introduction
- Background
- Bending
- Shear
- Torsion
- Confinement
- Execution
- Safety factors
- Conclusions
- Acknowledgment
The start

The work with the guidelines started 1998 in relation to a strengthening work of a rail road bridge

It was felt from the Rail Road authorities that a guideline was needed if the techniques should be accepted to be used on railroad and the like.
The start

The guideline is divided in four main parts

- Introduction part that explain the use of advanced composites for strengthening
- Comprehensive theoretical part that give a clear understanding of the design process
- Execution part which explain how the strengthening work shall be carried out
- Finally appendices with design examples and material data for use
The start

The most essential in the codes considered to be:

- Strengthening for bending
- Strengthening for shear
- Safety factors

But also fatigue, torsion and confinement are considered.

\[
f_d = \frac{f_k}{\gamma_m \gamma_n}
\]

Execution and quality control
Bending
Strengthening for bending – Failure modes

1. Compressive failure
2. Yielding, tensile reinf.
3. Yielding, compressive reinf.
4. Tensile failure, laminate
5. Anchorage failure
6. Peeling failure
7. Delamination

In general:

\[ M = A_s'f_y'\left(0.4x - d_s'\right) + A_s'f_y(d_s - 0.4x) + \varepsilon_f E_f A_f (h - 0.4x) \]
Bending

Strengthening for bending – Design

In general (depending on expected failure mode):

\[ M = A_s f_y (0.4x - d_s) + A_s f_y (d_s - 0.4x) + \varepsilon E_f A_f (h - 0.4x) \]
Introduction

Based on fracture mechanics

\[ l_a = l_{cr} \frac{0.2 f_{fd}}{\sqrt{f_{ct} E_f w/t_f}} \]
Bending

End-peeling

Shear

Peeling

\[ \tau_{\text{max}} = \frac{G_a P}{2 s E_c W_c} \left( 2 \ell + a - b \right) \left( a \lambda + 1 \right) \]

\[ \lambda^2 = \frac{G_a b_f}{s} \left[ \frac{1}{E_f A_f} + \frac{1}{E_c A_c} + \frac{z_0}{E_c W_c} \right] \]
Bending

Failure criteria

\[ \sigma_1 < f_{ct} \]

\[ \sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \left[ \frac{(\sigma_x - \sigma_y)}{2} \right]^2 + \tau_{xy}^2 \right]^{1/2} \]

\[ \sigma_x = \frac{M_x}{I_2} (h - x) \]
Shear - Design

Failure modes

1. Compressive failure in the concrete
2. Tensile failure (fibre) in composite
3. Anchorage failure
Shear - Design

In general:

$$V_d = V_c + V_s + V_f$$

How to calculate $V_f$?
Shear - Design

Derivation of $V_f$: Equilibrium equations gives:

$$V_f = 2t_f 0.9d(\sigma_\gamma \cot \alpha - \tau_\delta \eta)$$

Assumptions:
- The composite only take up force in the fibre direction
- The inclination of the shear crack, $\alpha = 45^\circ$
- The principal tensile strain is perpendicular to this plane

$$V_f = \sigma_{fe} \frac{A_f 0.9d(1 + \cot \beta)}{s} \sin \beta$$
Shear - Design

The effective stress can be expressed as:

\[ \sigma_{fe} = \sigma_f \cos^2 \theta = \varepsilon_f E_f \cos^2 \theta \]

and with:

\[ b_f = \frac{b_f}{\sin \alpha} \]

The following equation is obtained:

\[ V_f = 2t_f \varepsilon_f E_f 0.9d(1 + \cot \beta) \sin^2 \beta \cos^2 \theta \]
The following equation is obtained:

\[ V_f = 1.2 \tau_f \epsilon_f E_f 0.9d(1 + \cot \beta)\sin^2 \beta \cos^2 \theta \]
Torsion - Design

Similar to shear – however, different crack path

Examples for strengthen in torsion
Torsion - Design

Design

\[ \frac{1.2t_b b_f \varepsilon_ {fu} E_f}{s_f} = \frac{T}{2bh (\cot \alpha + \cot \beta) \sin \beta} + 1 \]

Different failure modes are also considered
Confinement - Design

Different shapes are considered
The design is valid for short columns i.e: \( l_c/h < 6 \).
Column Strengthening - Design

Design

\[ N_u = k_c \frac{A_c f_{cc}}{1 + k_{\phi} \Phi_{ef}} + k_s A_s f_{sc} \]
Execution and quality control

- Handling and protection
- Accidents measures
- Strengthening work
- Quality control

BEFORE STRENGTHENING
Examination of existing documentation, structure, loads and material data etc.

DURING STRENGTHENING
Surface Preparation
Remove weak concrete and contaminations, round corners when needed - make the surface dust and grease free. Concrete surface treated depending on strengthening material used:
- Laminates: Sandblasting
- Sheets: Sandblasting and grinding
- NSMR: Saw cuts in the concrete cover

Externally bonded reinforcement
All materials must be dust and solvent free and when applicable cleaned with a solvent before mounting

Bonding procedure
- Laminates: Apply primer when recommended. Apply adhesive on both laminate and the concrete surface. Mount together.
- Sheets: Apply primer. Level out the surface with putty when needed. Apply adhesive and mount the sheet in the wet adhesive - apply a new layer of adhesive, repeat the procedure for numbers of layers needed.
- NSMR: Apply adhesive or cement mortar in the cleaned and dry slot. Mount the NSMR laminate in the slot.

AFTER STRENGTHENING
Finishing layer
Paint, shotcrete, resistant to wear etc.
Fire Protection
Due to regulations and demand from client

QUALITY CONTROL (Before, during and after Strengthening)
Safety - Factors

Partial coefficients

Material properties

Safety class (1,2,3)

\[ f_d = \frac{f_k}{\eta \gamma_m \gamma_n} \]

\[ \gamma_m \]

\[ \gamma_n \]
Safety - Factors

Material properties is divided into:

\[ \gamma_{m1} : \text{Consider uncertainties in material characteristics} \]
\[ \gamma_{m2} : \text{Uncertainties in calculation model} \]
\[ \gamma_{m3} : \text{Consider the failure type} \]
\[ \gamma_{m4} : \text{Consider influence of control} \]
\[ \gamma_{m5} : \text{Consider short or long term loading} \]
\[ \gamma_{m6} : \text{Consider the implementation process, e.g laminates, fabrics etc.} \]

Safety class (1,2,3)

Class 1: \[ \gamma_n = 1.0 \]
Class 2: \[ \gamma_n = 1.1 \]
Class 3: \[ \gamma_n = 1.2 \]
Safety - Factors

Partial coefficients

Example:
Calculate the resistance parameter $\gamma_m$ for a composite strengthening with carbon fibre sheets in a hand lay-up application, in order to bear an increased traffic load. Strengthening is performed for increased bending moment capacity. Good control during implementation is expected.

Solution:
- high conformity between strength in test bodies and structure $\gamma_{m1} = 1.00$
- normal accuracy in calculation model $\gamma_{m2} = 1.00$
- ductile failure without bearing capacity reserve $\gamma_{m3} = 1.00$
- high control over materials and implementation $\gamma_{m4} = 0.95$
- carbon fibre as well as dynamic load $\gamma_{m5} = 1.05$
- hand lay-up, normal accuracy $\gamma_{m6} = 1.30$

Together this gives the safety factor:

$$\gamma_m = 1.00 \cdot 1.00 \cdot 1.00 \cdot 0.95 \cdot 1.05 \cdot 1.30 = 1.30$$
Field Applications

The design guideline has been used here
Conclusions

• Design guidelines are essential for increased use of FRP’s in the building industry

• We have noticed increased interest in the FRP strengthening method since the design guidelines were introduced

• It is recommended to use calculation examples in the guidelines for clarification

• The guidelines need to be a "living" document that should and can be changed depending on new knowledge.
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