Reinforcement and structural repair with FRP application in earthquake engineering

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Introduction

1. Sustainability in Civil Engineering
   - Before Construction: Design
   - In Function: Durability
   - After Damage: Maintenance and Repair
2. Repair Technology:
   - Materials: FRP, Concrete, Steel
   - Technique: Replacement, Reinforcement
3. Impact of Earthquake:
   - Monumental Structure: Historical Buildings
   - Infrastructure: Roads, Pipe lines, tunnels
4. Research Methodology
   - Laboratory: Health Monitoring
   - Computer Simulation: Finite Element Simulation
5. Future Studies
   - FRP application in Pipe treatment
   - FRP piles subjected to pressure movement (seismic activity simulation)

Sustainability in Civil Engineering

1. Before Construction
   - Construction Materials (Strength-Weight ratio, Insulation properties, Less foundations requirement)
   - Design Methods (Maintenance, Construction Time, Assembling/disassembling)
2. In Function
   - Durability (Maintenance, Corrosion Resistance)
   - Efficiency (Insulation Properties)
   - Health Monitoring
3. After Damage
   - Repair
   - Replacement
   - Reinforcement

GFRP Materials

	Fibre (E-Glass)	Matrix (Vinilester)
Elastic Modulus (MPa)	72400	3309
Tensile Strength (MPa)	4350	87
Elongation (%)	4.8	4.2

GFRP Materials

- Composite materials (Glass Fibre and Resin)
- Directional behaviour (Strong Direction / Weak Direction)
- Static Behaviour (high strength to weight ratio)
- Dynamic Behaviour (Damping ratio)
- Thermal Behaviour (Considerable Residual Resistance)

- Pultruded GFRP : Matrix 60% - Fibre 40%
- GFRP Shape: laminated configuration layers

GFRP Material-Practical Properties

- Needs less maintenance
- Due to its light density and ability to dissipate energy in seismic activities
- High strength and mechanical performance
- New concept of assembling and disassembling

GFRP Material-Practical Properties

- GFRP Materials
- High durability which provides potential to be applied in difficult environmental conditions (corrosive/seismic environment)
- Potential new concepts of construction:
  - Social housing
  - 3D print houses
  - Temporary housing
  - No foundations required
  - Proper water front/inside constructions
- Rehabilitation: new concept of use with more traditional materials (RC concrete, masonry and steel- for historical repair and mixed material applications like pipelines)

Use of FRP as reinforcement bar in concrete sheet samples
(from http://www.bpcomposites.com)

GFRP Material-Practical Properties

GFRP Materials

- More efficient construction procedures
- More durable performance, better dissipation of energy in earthquake, more deformability
- High flexibility, no welded action is required (unlike steel)
- It has been recognized in international technical design Codes: ASCE,CEN and ISO
- Reduces construction costs (lifetime cost):
  - less material is required,
  - less workman/hours is required
  - less heavy vehicle is used,
  - Shorter construction time
- Some discussion on FRP vulnerability to temperature/fire. Research by SEG and others (Correia et al. 2013, Al-Salloum et al. 2011, Chowdhury EU 2011) suggest high residual strength after temperature loading.

FRP as bumper illustrating material deformability
(From http://www.aliexpress.com)

GFRP Cost

Table 1 Cost of materials per unit force.

Material	Strength (MPa)	Cost (£/kN/m)	Cost ratio	Notes
Prestressing steel	1700	0.002	1	7-wire strand on coil
Reinforcing steel	460	0.006	3	Includes bending
GFRP	580	0.013	6.5	Excludes bending
Aramid fibre	2600	0.009	4.5	Fibre only
Aramid rope	2000	0.025	12.5	As a rope
AFRP	2000	0.025	12.5	As a pultrusion
CFRP	2000	0.025	12.5	As a pultrusion

(based on £1 = US$1.77 = €1.50, 2004 prices)

Berg et al. (2006)

Subject of the study:

The construction of an FRP reinforced concrete bridge deck using conventional construction technology

- Using FRP instead of steel resulted in:
- 57% savings in construction labour
- 60% increase in Material cost
- Savings in construction time and
- long-term benefits
- **reported to be cost-effective**, even with the high initial costs.
- Sustainability benefits in terms of cost…but environmental benefits now being investigated

Burgoyne(2007)

Durability issues with structures enforce repair cost

an apparently small amount of money and an ability to see into

"If structures are designed today and it takes 35 years before they need attention, who cares?":

Children

The initial-cost study steel are less expensive than FRP

What if steel is corroded? FRP is a valid alternatives

Sustainability of FRP

FRP Sustainability:

- Higher strength
- Lighter weight
- Higher performance
- Longer lasting
- Rehabilitating existing structures
- Potential for seismic upgrades
- Defence systems unique requirements
- Space construction
- Ocean environments

- Minimum resource use
- Low environmental impact
- Low human and environmental health risks
- Sustainable site design strategies
- Higher performance

Lee et al. (2009)

<u>Concept of Whole-Life-Costing analysis</u>

- Structural Lifetime – Cost of repair
- Discount rates – Predictive increase in repair and maintenance cost in future
- Delay costs – Interrupted Functionality Cost (such as oil and gas)

Ehlen (1999)

(no heavy vehicles and less labour costs)

GFRP Advantage in Earthquakes

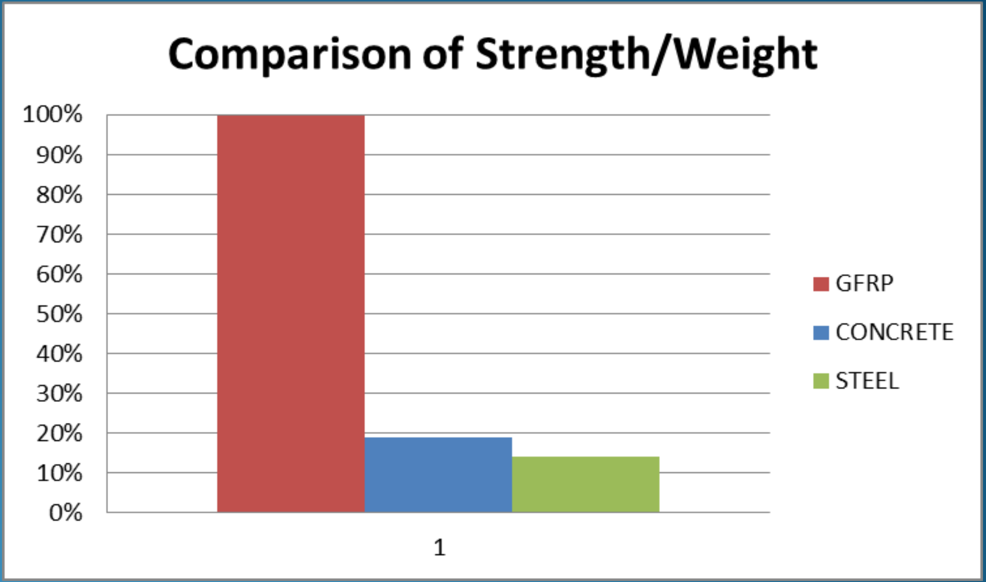
Benefit of GFRP with seismic activities is two folds:

High strength and low weight

High ratio of strength/weight has a

Significant effect when the structure is subjected to seismic activity Because the weight of the building times the earthquake acceleration defines earthquake load design. The GFRP can reduce the weight of building so the building will receive less earthquake force.

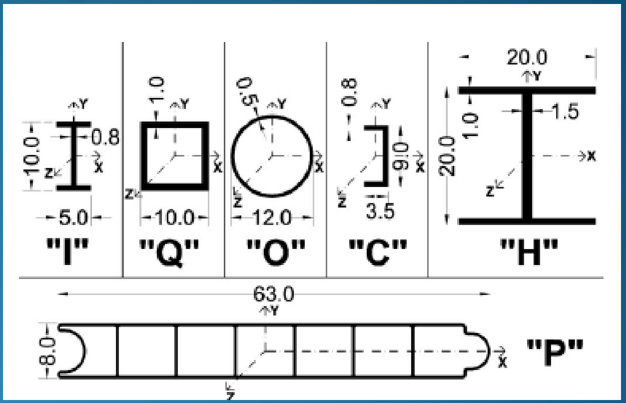
- Most New Zealand use of FRP remediation and repair rather than original construction with GFRP



Material	Typical strength	Unit weight	Strength/Weight Ratio
GFRP	400 MPa	1850 kg/m3	**0.216**
Portland Concrete	100 MPa (after 100 days)	2400 kg/m3	**0.0416**
Construction Steel	240 MPa	8000 kg/m3	**0.03**

GFRP Materials vs Traditional Materials

- <u>**Comparison of dynamic properties as structural element (Boscato and Russo 2009)**</u>
- GFRP
- Aluminium
- Steel
- The dynamic behaviour of structural elements (beam) is studied
- Different cross sections are studied
- For the simply supported condition, the damping ratio increases from 2.26%–3.4%
- Low weight of GFRP created a reduction in the fundamental frequencies
- GFRP performed efficiently in dynamic loading (structure is more flexible – low frequency- Less mass of structure- according to Newtonian Law less mass under acceleration means less load-displacement)



Structural element	Material	Fundamental frequency (Hz)
"*I*," J_{max}	GFRP	24.41
	Aluminum	26.79
	Steel	20.72
"*H*," J_{max}	GFRP	16.47
	Aluminum	20.04
	Steel	15.5
"*Q*"	GFRP	35.09
	Aluminum	41.77
	Steel	32.31
"*P*"	GFRP	11.9
	Aluminum	11.7
	Steel	9.07

GFRP Materials vs Traditional Materials

Comparison of FRP piles and Concrete Piles (Pando et al. 2003)

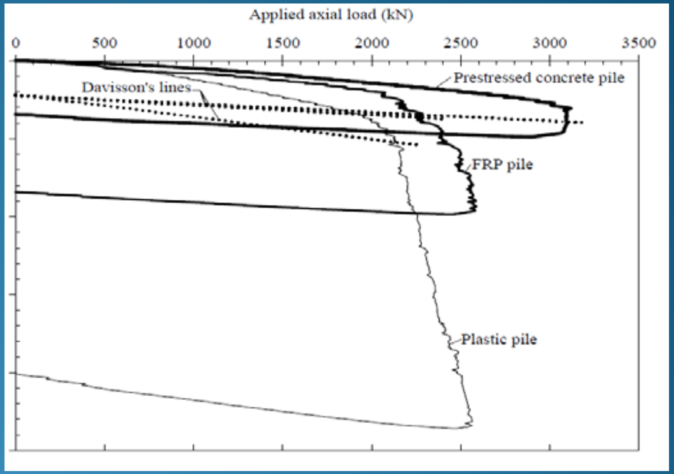
• Axial stiffness of prestressed concrete pile and the FRP piles are reported to be similar

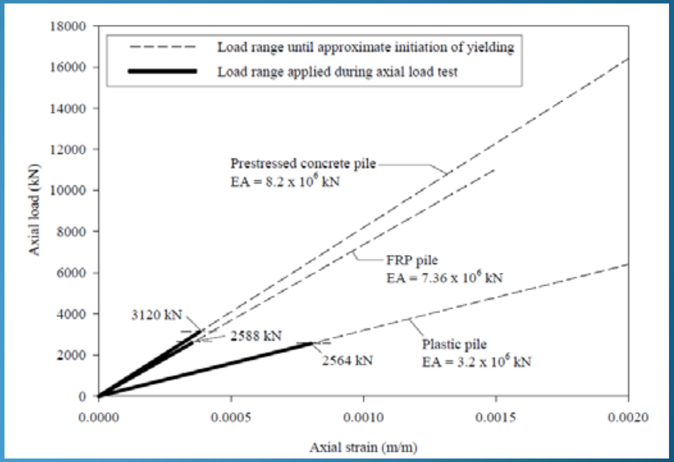
• Static Axial Capacity of prestressed concrete piles reported as 3090 kN while FRP piles reported as 2260 kN

• Toe resistance was 1854 kPa for concrete and 2564 kPa for FRP piles

• Load deflection was similar for both the prestressed concrete pile and the FRP pile

• Whilst the mechanical properties in both piles are similar, the sustainability benefits of GFRP are considered to be higher

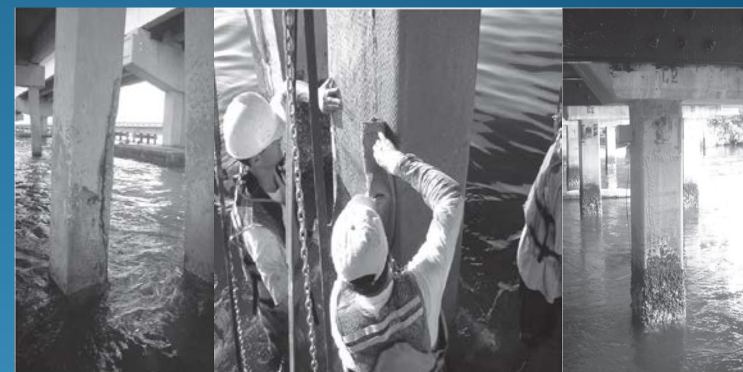




FRP Repair Technology

Techniques

- Protection against Corrosion:
  - Concrete Column: Wrapping
  - Concrete Piles : Wrapping
- Increase Strength:
  - Pipe lines: Wrapping



Repair Technology- Examples

Remedial laminated CFRP applications
Baronial Palace Lopez Y Royo Monteroni, Spain (circa 2005)

- Reinforcement of Historical Structure
- Vault Structure: Good for compression force/No tensile strength
- FRP provides tensile strength
- FRP working with existing materials

Repair Technology-Examples

Remedial laminated CFRP applications

Seismic Improvement of Supermarket Co-op in Poggio Renatico, Italy.

- Laminated CFRP increases flexural rigidity

Repair Technology-Examples

Temporary structure for the church of S Maria Paganica , L'Aquila, Italy in 2009 (Russo et al. 2010)

Permanent and temporary supporting scaffold structures

- Supportive truss and temporary structure
- GFRP is light and can be assembled in delicate places with low risk of damaging high valued historical building

Repair Technology

Permanent and temporary supporting scaffold structures

Temporary structure for the church of S Maria Paganica , L'Aquila .
(Russo et al.)

Supportive truss and temporary structure

Repair Technology

1. **Steel Fibre Reinforced Concrete for Layer Support in Pavement and Road Construction**

Application in concrete slab

The study dealt with two-dimensional slab used as pavement.

The slab was steel fibre reinforced concrete SFRC instead of ordinary reinforced concrete RC

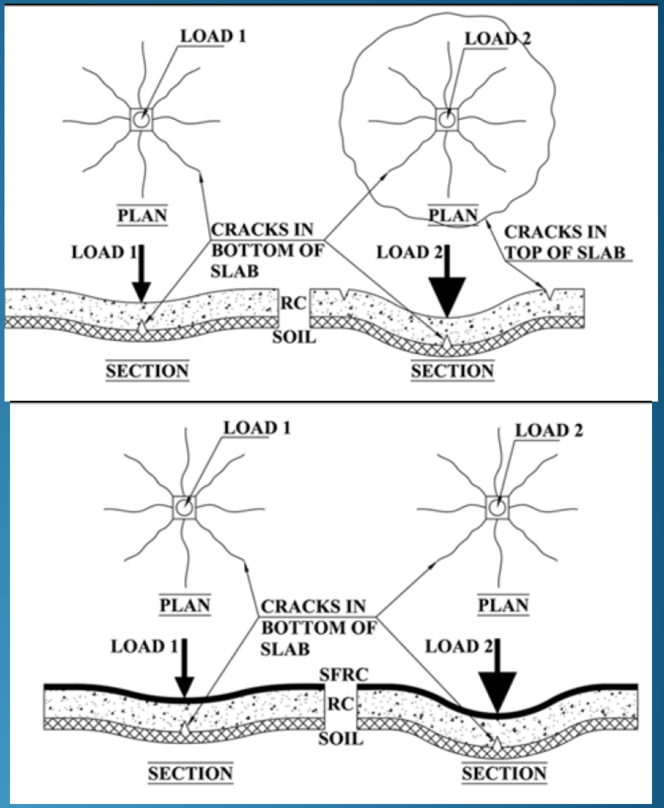
Different thickness of SFRC is considered

no cracks due to tensile stress on the upper face were detected.

Up to 32% increase in stiffness

Finite element analysis carried out and good agreement is reported

(Dal Cin et al. 2015)



Supporting SFRC Layer in Pavement (Dal Cin et al. 2015)

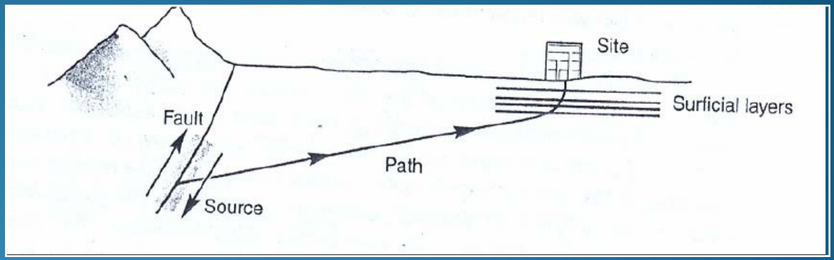
Impacts of Earthquakes

Earthquake Waves

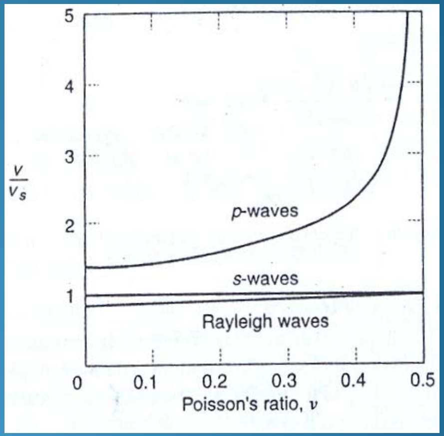
- Pressure waves
- Shear Waves
- Surface Waves

Resulting impacts

1. Geotechnical Faulting
    - Slope Failure
    - Differential settlement
2. Structural Vibration
    - Historical Structure
    - Towers (high weight of construction materials and low tensile strength)



(Kramer 1996)



Impacts of Earthquakes

Civil Structures vulnerable to Earthquake induced faults

- Oil and gas pipe lines
- Road pavement
- Tunnels
- Railways

FRP repair technology provides efficient repair and increases the strength

Impacts of Earthquakes

Dynamic loading on Historical Structures (Russo et al. 2012)

The structural safety is a challenging subject for a historical building.

There have been reports of sudden collapse of very famous historical towers subjected to earthquake:

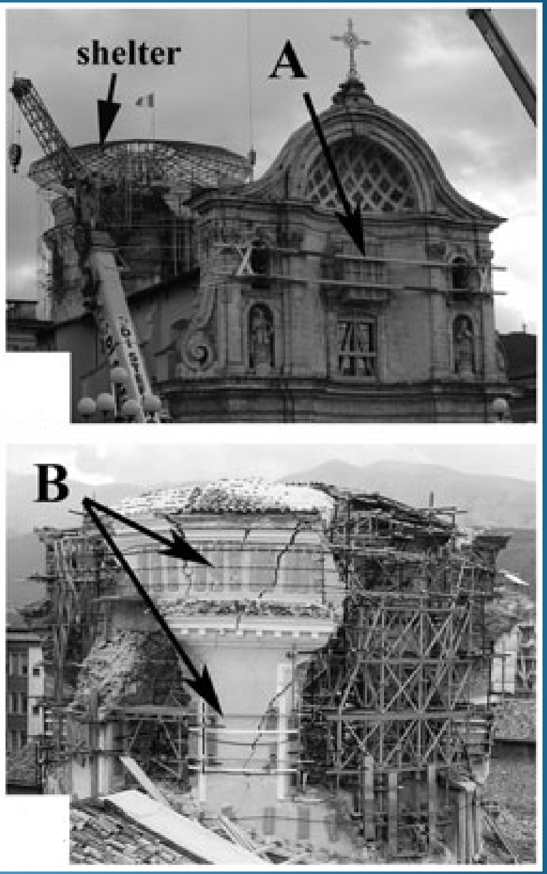
- The Bell Tower of San Marco in Venice
- The Civic Tower in Pavia

Seismic loading has a dangerous potential to cause damage and even collapse of such structures

- The large masses involved and
- The height at which the loading (weight) is distributed
- None or scarce tensile capacity

Case Study:

1. Anime Sante historical church in L'Aquila, Italy hit by earthquake in 2009
   - Ambient and seismic vibrations have been used to check damaged historic masonry structure
   - GFRP was installed to support damaged structure



Anime Sante historical church in L'Aquila (Russo et al. 2012)

SEG Research Outlines on GFRP

Durability and residual strength of GFRP is researched (Russo et al. 2015)

- Several thermal cycles applied to GFRP samples and residual strength were measured
- Laboratory tests with Acoustic Emission Sensor and strain gauges were conducted and finite element analysis performed to investigate samples in details
- While the weak points of GFRP are claimed to be their weakness against heat, in this research considerable residual strength (more than 75% of the original strength) was observed after sever thermal loading.
- Failure mechanism was investigated and suffice deformation before failure was observed. The material behave brittle (compare to steel) but shows some ductility (more than concrete)

Future Research on FRP Pipes

Research will be conducted through
- Laboratory: Modelling in soil box
- Finite Element Simulation

1. Durability of FRP Pipes
   - In corrosive environments
   - In high temperature
2. Assessment of FRP Pipes in Earthquakes
   - Investigation of earthquake induced cracks
   - Investigation of effects of differential settlement
3. Developing Repair Strategy
   - Wrapping with FRP materials, Do not need Pipes to be offline
   - Comparison with traditional method/physical replacement

Future Research on FRP Piles

1. Investigation of GFRP Piles in Corrosive Environment
   - Durability : Service Load
   - Functionality: Extreme Load (Earthquake)
2. Strength Comparison between GFRP and Concrete Piles
3. Investigation of GFRP Sheet Piles Subjected to Earthquake
4. Use of construction waste materials in GFRP production
5. Full sustainability assessment of FRP materials

Sustainability benefits of GFRP

1. High strength/weight ratio
2. High durability/ less maintenance (cost)
3. Less foundation preparation than traditional concrete
4. More corrosion resistant than concrete and steel in salty water and acidic environments
5. Significant remedial applications (reinforcement, repair, replacement)
6. Construction time (less weight, modular, assembling, disassembling, less labour and transport)
7. Heat/Noise insulation
8. Embodied Energy (Less material intensity)
9. Potential for recycled and recovered material in FRP

Thank you for your attention… and wishing Christchurch enhanced flexibility and durability into the future!