# Comparison of FRC and ECC in a Composite Bridge Deck

Rasmus Walter, PhD Candidate
*Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark*

V.C. Li, Supervisor
*Department of Civil and Environmental Engineering, The University of Michigan, Ann Arbor, USA*

H. Stang, Supervisor
*Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark*

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ABSTRACT: A new type of composite bridge deck is currently under research. The concept is aimed at achieving composite action through the adhesion between a thin cement-based layer and a steel plate without using traditional shear connectors. This paper presents experimental and numerical work carried out on composite beams exposed to negative bending. Two types of overlay material are tested: Engineered Cementitious Composites (ECC) and fibre reinforced concrete (FRC). Two set-ups designed to test composite beams using ECC and FRC are presented and analysed using numerical methods.

*Keywords: ECC, FRC, Testing, Numerical modelling, debonding*

## 1 INTRODUCTION

A typical orthotropic steel bridge deck in Europe consists of a 12mm steel plate with supporting ribs welded to the bottom face. This type of bridge deck suffers significantly from increasing traffic loads, particularly from heavy trucks. The increased traffic intensity and higher wheel loads result in fatigue cracks in both welded structures and surfacing. Therefore the development of an entirely new concept of deck systems is of interest. Increasing the local stiffness of a typical orthotropic steel deck, using a cement-based overlay to form a composite plate, is the subject of an ongoing research project. The cementitious overlay increases the local stiffness significantly and thus might be effective in increasing the fatigue life of the bridge deck. It is hoped, that the concept under development can either be applied to retrofitting or in the design of new bridge decks.

A typical deck according to the proposed system consists of a 40-60mm cement-based overlay bonded to an 8-14mm steel plate (Walter et al. 2003a). Whereas conventional composite constructions achieve composite action by means of mechanical fasteners, the idea here is to achieve composite action through adhesion only. The motivation for a simple shear connection between the overlay and the underlying steel plate is to reduce labour cost.

The steel plate is sandblasted prior to casting of the overlay in order to have a clean surface and thus minimizing the risk of defects. For this system, the interface between the concrete overlay and the steel plate is of major concern. Negative bending can cause vertical cracking of the overlay, which causes large tensile stresses perpendicular to the steel-overlay interface. Such interfacial tensile stresses, eventually leads to debonding between the overlay and the underlying steel deck. The significance of an overlay crack in relation to debonding is discussed in Walter et al. (2003b). The formation of multiple cracks under negative bending in the overlay delays the development of a macro-crack, thus possibly preventing debonding in the deformation range considered. In this paper emphasis is put on comparison of the performance using ECC and FRC as the overlay material.

Both ECC and FRC can be characterized as fibre reinforced cement-based composites. The fundamental mechanical difference between them, are their behaviour in uni-axial tension. ECC shows strain hardening behaviour and forms multiple cracks. In contrast, FRC is characterized as a tension softening material forming a single crack in uni-axial tension.

Two test methods to examine the performance of ECC and FRC in composite with steel, subjected to negative bending, will be presented. Attention is paid to debonding, crack spacing and width. Since debonding mainly is caused by a macro-crack in the overlay the use of ECC may prevent debonding in the deformation range considered for structural purposes and may be of significant interest in the application under consideration.

Furthermore, the two test set-ups will be studied numerically using the finite element method. The modelling will concentrate on the different cracking behaviour of FRC and ECC.

## 2 EXPERIMENTAL PROCEDURES

### 2.1 *Materials and specimen preparation*

The well-known advantage of fibre reinforced concrete is its ability to sustain larger deformation after the first crack is formed. The fibres will typically stay unbroken after the first crack is formed and the fibres, that cross a crack, will resist further opening. Depending on the crack bridging effect, fibre reinforced composites can show different failure modes. If the average fibre bridging effect is increasing during crack initiation and propagation, then multiple cracks can form. This behaviour is also known as strain hardening. On the other hand, if the fibres cannot carry anymore load after the formation of the first crack, then further deformation is governed by opening of a single crack. This behaviour is called tension softening. In the following composite beams comprising materials with tension softening and strain hardening behaviour, FRC and ECC respectively, are examined.

The ECC material contains 2% by volume poly-vinyl-alcohol (PVA) fibres in random orientation along with standard mortar matrix components, cement, fine aggregate (0.1 mm nominal grain size), water, and various admixtures to improve the fresh properties of the mixture. The ECC material exhibits strain-hardening behaviour in tension. This behaviour, is achieved through a micro-mechanic design approach, for further details, see Li (2002).

The FRC material used in this study was composed of cement, coarse aggregates (16 mm nominal grain size, fine aggregates, admixtures and water. A fibre volume of 1% hooked-end steel fibres was used.

The specimens were prepared by first sand blasting the steel surface and finally casting the cement-based layer. For both the ECC and FRC material, the same specimen geometry is used, however the two test set-ups differs slightly as described in the following sections.

### 2.2 *Experimental set-up for ECC composite beams*

A composite beam subjected to three-point bending is used as the primary test set-up. The composite beam consists of a steel plate and a thin cement-based layer.

When testing the ECC composite beam, emphasis is put on observation of crack spacing, crack width and debonding between the steel plate and overlay. Crack width during loading is monitored using a microscope (Olympus OVM1000N) having a magnification of 200x. A single crack is selected and measured through the experiment. Debonding between the steel plate and ECC is measured using two LVDTs mounted on either side, 50mm from the load point. The LVDT is attached with one end to the steel plate and the other to the ECC layer. It measures any elastic deformation between the two end points and additionally captures any steel-ECC interfacial cracking. Testing of the composite beam is performed in closed-loop control, using the stroke as the controlling parameter. The set-up is depicted in Figure 1.

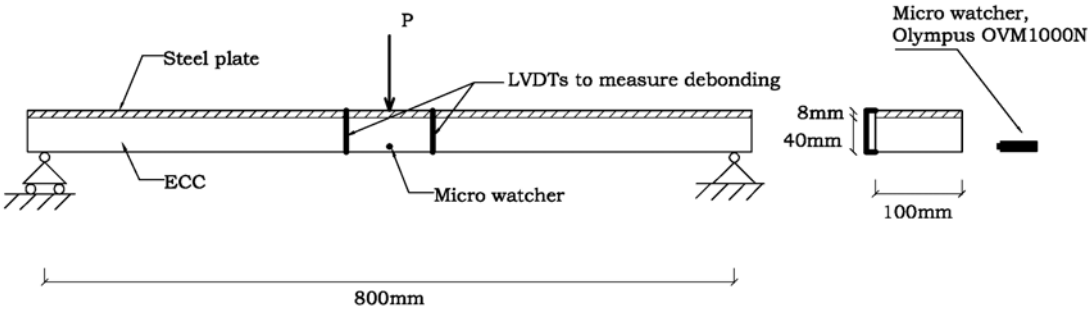

Figure 1. Experimental set-up of the ECC Composite beam. Two LVDTs are mounted 50mm on either side from the load point to detect and measure possible debonding. A Micro watcher is used to measure the crack width during the experiment.

### 2.3 *Experimental set-up for FRC composite beams*

The steel-FRC composite beam is expected to form one discrete crack in the overlay at midspan, where the negative bending moment attains its maximum. In this case, attention is put on interfacial debonding and the opening of the overlay crack (COD). Again, to detect and measure possible debonding, two LVDTs are mounted on either side, 50mm from the load point to record steel-FRC interfacial cracking. A clip gage is mounted on the bottom face of the beam measuring the crack opening displacement COD of the overlay crack. To ensure stable crack growth through the experiment, this signal is used as the controlling parameter in the closed-loop control of the experiment.

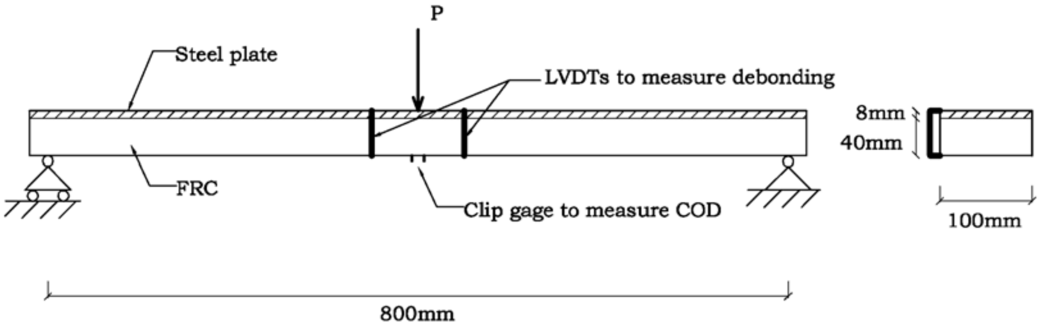

Figure 2. Experimental set-up of the FRC Composite beam. Two LVDTs are mounted 50mm on either side from the load point to measure possible debonding. A clip gage is used to measure the opening of the overlay crack (COD). The clip gauge signal is used for closed loop control.

## 3 EXPERIMENTAL RESULTS

The experimental results for the FRC and ECC composite beams are shown in Figure 3(a) and (b), respectively. In the case of the FRC beam, the failure mode is dominated by a single crack. The result from a typical experiment is presented in a Moment-COD diagram, cf. Figure 3(a). The failure mode of the ECC composite beam is characterized by formation of multiple cracks along the beam. A typical experimental result from a test on an ECC composite beam is presented in a moment vs. midspan deflection diagram, cf. Figure 3(b). The difference in scaling of the two y-axes, representing the negative bending moment, should be noted when comparing the two results. It is seen from Figure 3 (a) and (b), that the ECC composite beam exhibits a more ductile behaviour when exposed to negative bending. Cracking of the overlay is initiated for the same negative bending moment in the two cases, approximately around 300kNmm. In the case of the FRC composite beam a threshold is observed for a moment value of around 400kNmm. For increased opening of the overlay crack, COD, the moment tends to be more or less constant. On the contrary, for the ECC composite beam, an increase of the moment is observed for increased deflection, until the point where the steel plate starts to yield. In Figure 3(b) also the crack width of the first crack of the ECC is plotted versus the deflection staying in the range of

10-30 micrometer. To compare the two tests, the end point of the FRC test, which corresponds to the maximum COD value shown in Figure 3(a), is plotted in the ECC graph, cf. Figure 3(b). Since this point wasn't measured during the experiment, it is calculated using numerical methods and explained later in the paper.

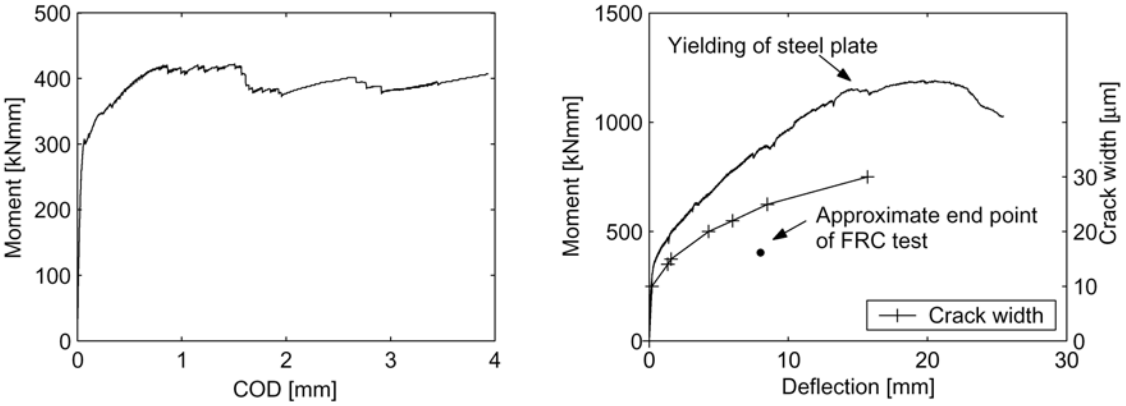

Figure 3. Typical experimental results (a): FRC and (b): ECC. Note that the FRC composite beam is presented by load vs. COD and the ECC composite beam is presented by load vs. deflection. The moment is calculated by M=1/4PL.

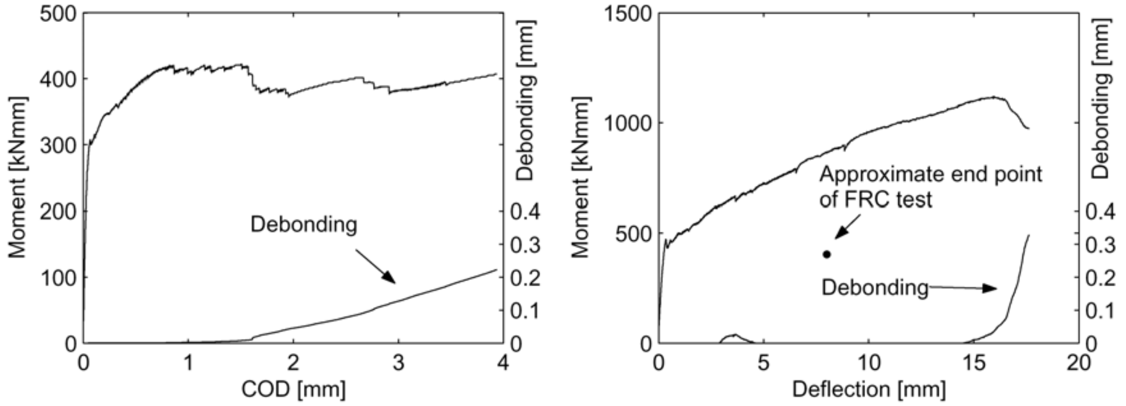

Figure 4. Typical experimental results for (a): ECC and (b): FRC.

Debonding of the overlay, measured using LVDTs, are shown for the FRC and ECC composite beams in Figure 4 (a) and (b) respectively. The normal stresses perpendicular to the interface, for an un-cracked specimen in the set-up considered, are compressive and are not critical for the bond. When a macro-crack forms and propagates in the overlay, it will cause a critical change in the interfacial normal stresses, changing them from compressive to tensile. For any further deformation of the beam, debonding of the overlay takes place in a combination of shear and normal tensile stresses. This mixed mode of shear and normal stresses is dominated by normal tensile stresses, see e.g. Walter (2003b) for further details.

The significant relation between an overlay macro-crack and debonding is clearly illustrated in Figures 4(a)-(b). The FRC composite beam develops a macro-crack at an early stage compared to that of ECC and debonding is observed for a COD value around 1mm. In contrast, the ECC-steel interface remains intact even for large deformations.

## 4 NUMERICAL MODELLING

The experiments described in the previous sections are analysed using FEM. Cracking of the overlay and debonding characterize the nonlinear behaviour of the FRC and ECC composite beams. For the ECC composite beam, yielding of the steel plate also needs to be taken into consideration. The modelling is carried out using a two-dimensional composite beam model. The model consists of a steel plate and an overlay either of FRC or ECC. The overlay-steel interface is modelled using standard interface elements, implemented in the applied software package DIANA. The modelling concept and the applied mesh is given in Figure 5.

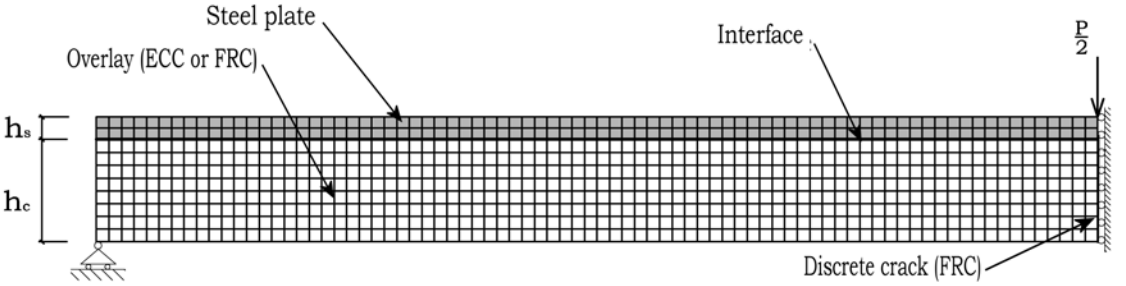

Figure 5. Half beam mesh used in FEM calculation of the experimental set-up. The thick line represents the interface between the overlay and steel plate. In the case of FRC a discrete crack is modelled at midspan also using interface elements.

Debonding takes place in a mixed mode, represented by normal and shear stresses. A multi-interface model is applied, developed by Lourenço & Rots (1997). This model takes into account softening of normal and shear stresses acting at the interface. As input, a failure envelope of Mohr-Coulomb type is applied. Furthermore, fracture energy of pure mode I and II is given as input and the two modes are coupled in an isotropic softening manner, meaning that the percent of softening in e.g. mode I is the same in mode II, see e.g. Lourenço & Rots (1997) for further details.

Cracking of the overlay is modelled differently in the two cases considered. In the case of a FRC overlay a discrete crack at L=1/2 is modelled while multiple cracking is considered in the case of an ECC composite beam. The following two sections describe the constitutive modelling of the materials.

### 4.1 *Constitutive modelling of ECC*

Modelling of the ECC overlay is carried out using a crack band model. This is a modification of the so-called fictitious crack model by Hillerborg et. al. (1976), developed by Bažant & Oh (1983). The material is modelled in three phases cf. Figure 6.

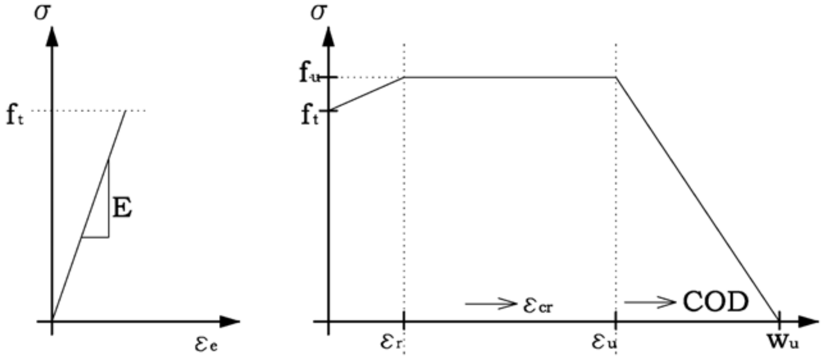

Figure 6. Constitutive modelling of ECC. The material is described in three phases: a linear elastic range, a strain hardening range and a linear stress-crack opening relationship.

For small deformations - the first phase - the material is assumed to behave elastically, having an elastic modulus denoted E. Second phase is the strain-hardening phase, described by a stress-strain relationship. In this phase the total strain of the material consist of two strain parts, an elastic strain $\varepsilon_e$ and a cracking strain $\varepsilon_{cr}$. At some point the tensile capacity is exhausted, due to the fact that at a certain crack, the fibre bridging has reached its load carrying capacity, and softening takes place. At this point the material moves from a stress-strain stage into a stress-crack opening stage. Similar constitutive modelling of ECC has been carried out by Kabele (2001).

### 4.2 *Constitutive modelling of FRC*

Modelling of the FRC composite beam is carried out considering a single crack in the overlay, modelled using interface elements. A large amount of work has been carried out modelling FRC and it turns out that a bi-linear stress-crack opening relationship provides reasonable results, see e.g. J.F. Olesen (2001). The constitutive description of the FRC material consists of two parts: a linear elastic and a bilinear tension softening part cf. Figure 7.

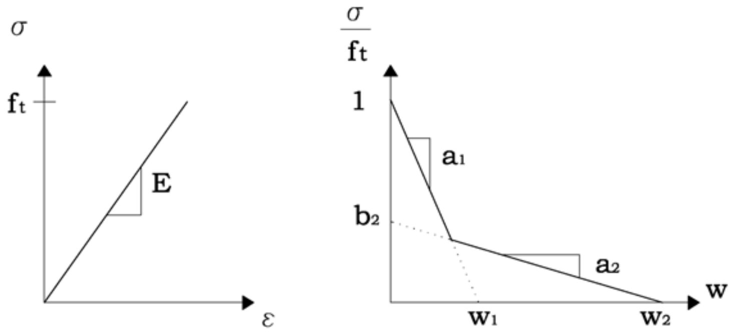

Figure 7. Definition of parameters of a bilinear stress-crack opening relationship, used in the constitutive modelling of FRC.

The two line segments has a slope of $a_1$ and $a_2$ respectively. The two parts of the bi-linear stress-crack opening relationship are conceptually associated with the concrete cracking and the fibre bridging, respectively.

### 4.3 *Model validation*

The two FE-models are validated using the experiments carried out on the ECC and FRC composite beams. The models are validated fitting the numerical results to the experiments, cf. Figure 8. The curves are fitted manually using trial and error. As seen good agreement can be achieved between the model and the experiments performed on FRC and ECC composite beams.

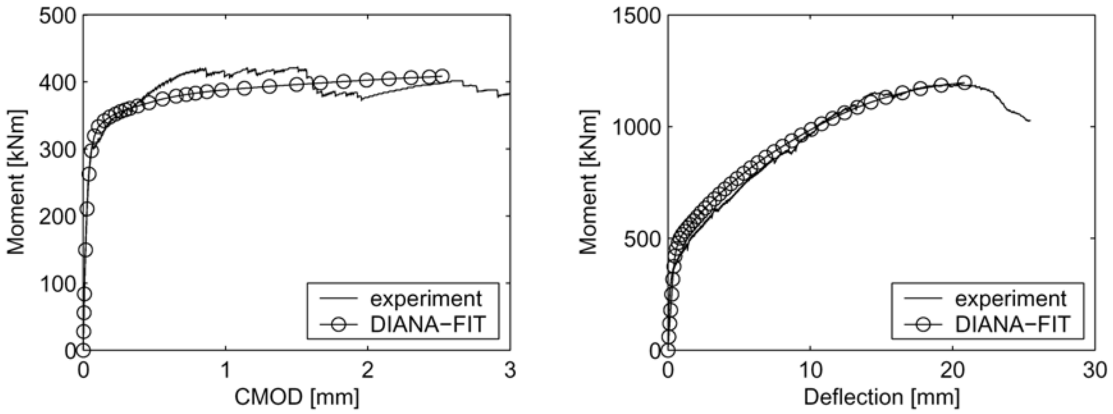

Figure 8. Examples on data fitting FE-model to (a): FRC composite beam and (b): ECC composite beam

The values used in the data fitting are given in Table 1. The interface values are the same in the ECC and FRC case and given by a Mohr-Coulomb failure envelope with a tensile strength $f_t$, cohesion $c$, slope $\tan(\varphi)$ and a pure mode I and II energy: $G_{f,I}$ & $G_{f,II}$. The material properties of ECC and FRC can be determined independent using various reference tests. For the FRC material, the standard three point bending test and the wedge splitting tests has been applied. In the ECC case uni-axial reference tests has also been carried out. The material properties from Table 1 are closely related to the values obtained in the reference tests.

Table 1. Values used for ECC and FRC composite beams in data fitting.

| ECC | E [MPa] | $f_t$ [MPa] | $f_u$ [MPa] | $\varepsilon_r$ [%] | $\varepsilon_u$ [%] | $w_u$ [mm] |
|---|---|---|---|---|---|---|
| Value: | 20000 | 4.0 | 6.0 | 0.3 | 2.5 | 4.0 |
| FRC | E [MPa] | $f_t$ [MPa] | $a_1$ [mm$^{-1}$] | $a_2$ [mm$^{-1}$] | $b_2$ | |
| Value: | 30000 | 3.5 | 10 | 0.2 | 0.9 | |
| Interface | $f_t$ [MPa] | c [MPa] | tan(φ) | $G_{f,I}$ [N/mm] | $G_{f,II}$ [N/mm] | |
| Value: | 2.9 | 3.5 | 1.0 | 0.1 | 0.1 | |

### 4.4 *Numerical comparison between ECC, FRC, concrete and the steel plate.*

Finally, a numerical comparison is carried out between the ECC and FRC Composite beams, a plain concrete composite beam and the steel plate cf. Figure 9. For the ECC and FRC composite beam, the parameters in Table 1 is used. In the case of the plain concrete composite beam, the same modelling concept and values are used except the $b_2$ value, which is taken as 0.1. This parameter is believed to represent the fibre contribution in the bilinear tension-softening diagram and it has been chosen to be significantly lower than the value for FRC.

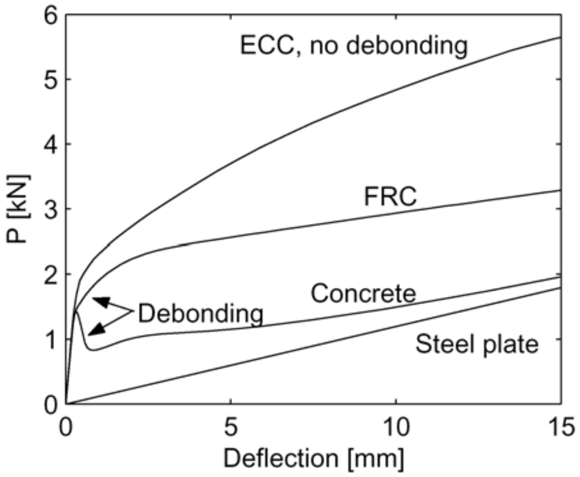

Figure 9. Numerical comparison between: ECC, FRC, concrete and the steel plate

It is seen from Figure 9 that debonding in the case of a FRC or concrete overlay starts significantly earlier compared to the ECC composite beam. In fact the ECC composite beam is predicted not to debond for the loads applied. Furthermore, the configuration with a plain concrete overlay gets close to the line representing the steel plate for a deflection greater than 5mm.

## 5 CONCLUSIONS

Two fibre reinforced composites having a tension softening and a strain hardening behaviour (FRC & ECC), has been used in the study of composite beams. Two test set-ups designed to investigate the composite beams has been presented. Emphasis was put on crack width and debonding. The ECC beams exhibits a more ductile behaviour with small crack widths and late debonding compared to the FRC composite beam.

Numerical modelling has been carried out on the ECC and FRC composite beam using the finite element method. The models where validated through the experiments. The numerical results were fitted to the experimental results. A good agreement between the model and the experiments was obtained.

## 6 ACKNOWLEDGEMENTS

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**Rasmus Walter, PhD Candidate**
Technical University of Denmark
Department of Civil Engineering
Brovej
2800 – Lyngby – Denmark
Tel. : + 45 45251766
Fax : + 45 45258832
E-mail: rw@byg.dtu.dk

**Prof. dr. V. C. Li, Supervisor**
University of Michigan, E-mail: vcli@engin.umich.edu
**Prof. dr. H. Stang, Supervisor**
Technical University of Denmark, E-mail: hs@byg.dtu.dk