

APPENDIX A: BEAM DESIGNATION LEGEND

BEAM DESIGNATION LEGEND

CON	- Control Beam. Number following CON is sample number
CSGF	- Clark-Schwebel Glass Structural Grid reinforcing for flexure only(F). Number following CSGF is sample number.
CSGFS	- Clark-Schwebel Glass Structural Grid reinforcing for flexure and shear(FS). Number following CSGFS is sample number.
CSGS	- Clark-Schwebel Glass Structural Grid reinforcing for shear only (S). Number following CSGS is sample number.
FCF	- Fyfe Carbon system (Tyfo) reinforcing for flexure only. Number following FCF is number of layers of reinforcement. Number following dash is sample number.
FCFS	- Fyfe Carbon system (Tyfo) reinforcing for flexure and shear. Number following FCFS is number of layers for both shear and flexural laminates. Number following dash is sample number.
45FCS	- Fyfe Carbon system (Tyfo) reinforcing for shear at 45 degrees. Since fibers are also wrapped across tension side, they provide significant flexural strengthening as well. Number following 45FCS is number of layers. Number following dash is sample number.
FGF	- Fyfe Glass system (Tyfo) reinforcing for flexure only. Same as FCF, but glass rather than carbon.
FGFS	- Same as FCFS, but glass system rather than carbon.
45FGS	- Same as 45FCS, but glass system rather than carbon.
MBCF	- Same as FCF, but Master Builders Carbon system (M-Brace).
MBCFS	- Same as FCFS, but Master Builders Carbon system (M-Brace).
MBGF	- Same as FGF, but Master Builders Glass system (M-Brace).
MBGFS	- Same as FGFS, but Master Builders Glass system (M-Brace).
MBG2F1S	- Two layers of Master Builders Glass system (M-Brace) for flexure, and one layer for shear.
MCF	- Same as FCF, but Mitsubishi Carbon System (Replark).

- MCFS - Same as FCFS, but Mitsubishi Carbon System (Replark).
- 45MCS - Same as 45FCS, but Mitsubishi carbon system (Replark).
- 90MCS - Mitsubishi carbon system (Replark) reinforcing shear only. Fibers run vertically (@ 90 degrees to longitudinal axis of beam) on side and tension side of beam similar to a U-shaped stirrup. No flexural strengthening is provided (other than transverse strength of the laminate). Number following 90MCS is number of layers. Number following dash is sample number.
- SCF - Sika (Carbodur) carbon system reinforcing for flexure only. All are one layer only. Number following SCF is sample number.
- SCFS - Sika (Carbodur) for flexure (one layer only) and Sika/Hexcel (SikaWrap) for shear reinforcing. Number following SCFS is number of layers of shear reinforcement. Number following dash is sample number.
- SHCF - Sika/Hexcel (SikaWrap) carbon system reinforcing for flexure only. Number following SHCF is number of layers. Number following dash is sample number.
- SHCFS - Sika/Hexcel (SikaWrap) carbon system reinforcing for flexure and shear. Number following SHCFS in number of layers of both shear and flexural laminate. Number following dash is sample number.
- 45SHCFS - One layer of Sika (Carbodur) for flexure and one layer of Sika/Hexcel (SikaWrap) ± 45 degree glass grid for shear. Glass shear reinforcement is provided in similar to 90 MCS (U-shaped stirrup), but fibers run at ± 45 degrees. Glass grid does not extend into center of beam, therefore it does not provide any increase in flexural strengthening.

APPENDIX B: TYPICAL FAILURE MODES

1 LAYER REINFORCED FOR FLEXURE:



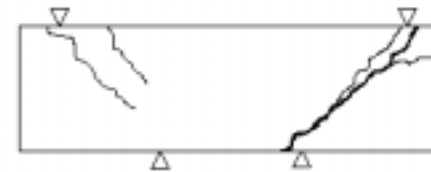
Many flexural cracks appear. Beam fails in shear with debonding at either end of laminate.

2 LAYER REINFORCED FOR FLEXURE:



Flexural cracking followed by flexural failure of the concrete and debonding of the laminate at ends of beam.

3 LAYER REINFORCED FOR FLEXURE:



Beam fails in shear with little presence of flexural cracking. Beam is clearly over reinforced.

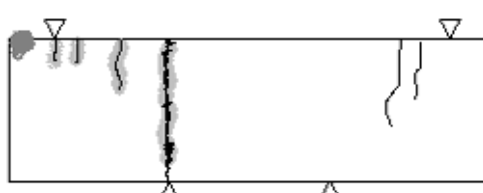
Figure B.2.1.3: Typical failure modes and crack patterns for flexurally reinforced MBrace™ carbon beams.

1 Layer - flexure and shear:



Obvious flexural cracking combined with transverse failure of shear laminate and eventually flexural failure of the laminate as well. Transverse failure occurs in shaded areas.

2 Layer - flexure and shear:



Flexural cracks appear outside of center of span. Beam fails in flexure with transverse shear laminate failure and eventual failure of the longitudinal laminate. Debonding occurs at end of laminate at which the failure occurs.

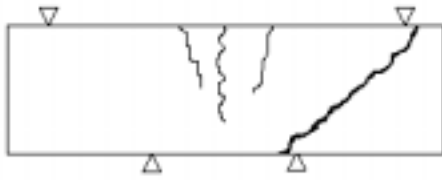
3 Layer - flexure and shear:



Little or no flexural cracking. Beam fails in shear with transverse failure of shear laminate. Debonding occurs at both ends of flexural laminate.

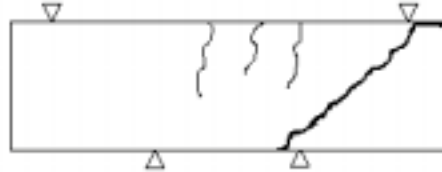
Figure B.2.2.3: Typical failure modes for MBrace™ carbon flexure and shear at 90° reinforced beams.

1 LAYER REINFORCED FOR FLEXURE:



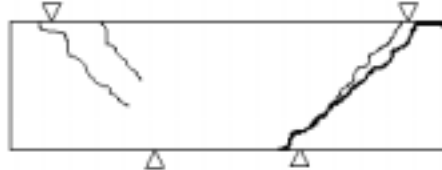
Flexural cracks form, however the beams eventually fails in shear.

2 LAYER REINFORCED FOR FLEXURE:



Flexural cracks are light. Beam fails in shear with the FRP pulling out some of the concrete near the ends of the beam.

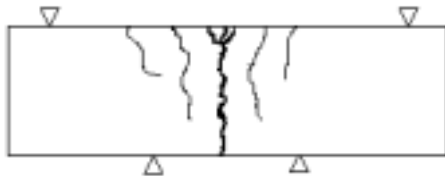
3 LAYER REINFORCED FOR FLEXURE:



Beam fails in shear with little presence of flexural cracking. Beam is clearly over reinforced. FRP pulls out at ends of beams similar to 2 layer beams.

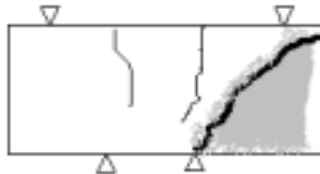
Figure B.3.1.3: Typical failure modes for Replark® beams reinforced for flexure only.

1 Layer - flexure and shear:



Concrete and FRP fail in flexure. Fibers providing flexural strengthening break. Many flexural cracks appear. Shear reinforcement splits transverse to fibers where crack in concrete exist.

2 Layer - flexure and shear:

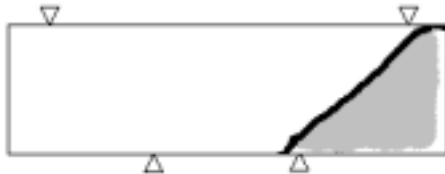


Beam End



Fewer flexural cracks appear. FRP pulls off concrete (shaded area). Beam fails in shear with cracking at the end of the beam. Some concrete crushes under loading points.

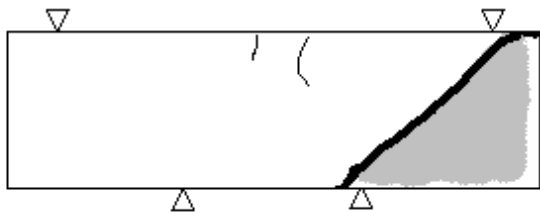
3 Layer - flexure and shear:



No flexural cracking. Laminate fails transversely and debonds. Concrete fails in shear following laminate failure. Again concrete crushes at point of loading.

Figure B.3.2.3: Typical failure mode and crack patterns for beams reinforced with Replark® for flexure and shear at 90°.

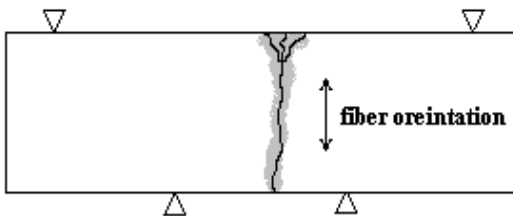
45° shear reinforced:



Laminate pulls off or debonds (shaded area) and beam fails in shear. In the one and two layer beams flexural cracks exist, but do not propagate out from under the composite.

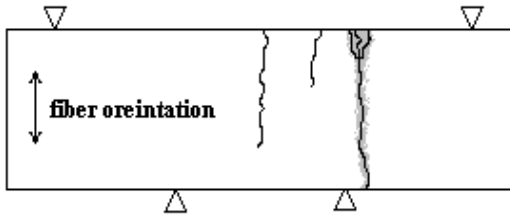
Figure B.3.3.3: Typical crack pattern and failure mode for beams reinforced at 45° for shear with Replark.

1 Layer - 90° shear reinforced:



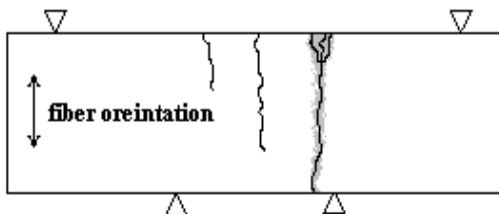
Beam fails in classic flexure. Laminate splits transversely at point of cracking (shaded area).

2 Layer - 90° shear reinforced:



Beam fails in flexure, but not in middle third of beam. Laminate again splits at points where cracks occur in concrete.

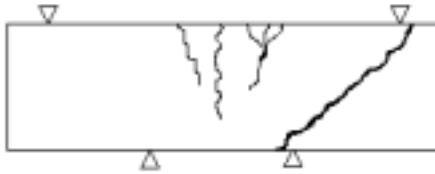
3 Layer - 90° shear reinforced:



Beam fails in flexure in middle third, but closer to loading points than 1 layer beams. Again laminate fails transversely at points where cracks occur.

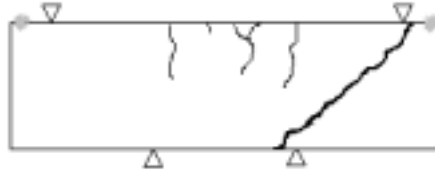
Figure B.3.4.2: Typical crack patterns and failure mode for beams reinforced with Replark® for shear at 90°.

1 LAYER SIKAWRAP:



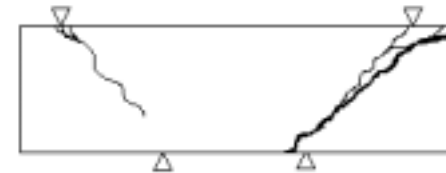
Flexural cracks form, however the beams eventually fails in shear.

2 LAYER SIKAWRAP:



Flexural cracks are light. Beam fails in shear with signs of stress in the resin at the ends of the flexural laminate(shaded).

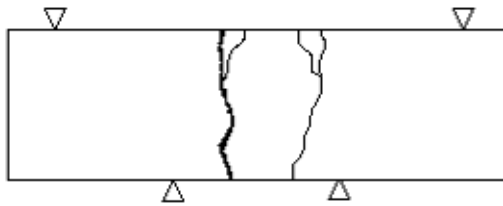
CARBODUR:



Beam fails in shear with little presence of flexural cracking. Beam is clearly over reinforced. Cracking at the end of the beam due to concentrated stress is observed.

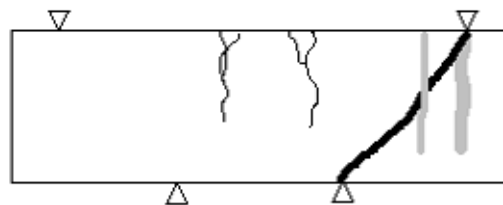
Figure B.4.1.3: Typical cracking and failure modes for beams reinforced for flexure only with Sika carbon products.

1 Layer - SHCFS:



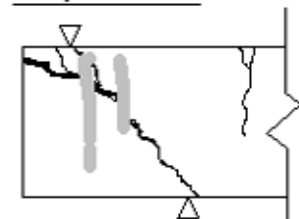
Flexural cracking originating along edge of shear laminate. Eventual flexural failure of concrete and laminate.

2 Layer - SHCFS:



Flexural cracking starts very similar to one layer beams (along shear lam. edge). Shear laminate splits parallel to fiber orientation (shaded) and beam fails in shear.

1 Layer - SCFS:

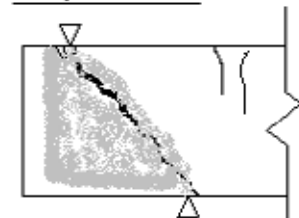


End of Beam

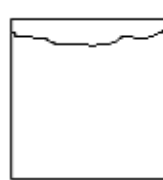


Flexural cracking is very light. Failure occurs due to shear cracking and concentrated stresses at the end of the flexural FRP causing splitting of the end of the beam. Splitting of the shear laminate was also observed (shaded area).

2 Layer - SCFS:

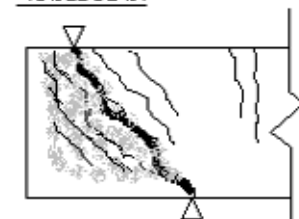


End of Beam

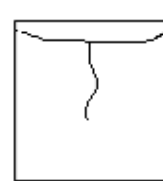


Flexural cracking is very light. Failure occurs due to shear cracking and pulling off of shear laminate (shaded area). Concentrated stresses at ends of flexural FRP cause cracking at end of beam.

45SHCFS:



End of Beam



Flexural cracking is very light. Failure occurs due to shear cracking and pulling off of shear laminate (shaded). Shear cracking in concrete is visible through the laminate. Cracking at end of beam is also light.

Figure B.4.2.3: Typical cracking and failure modes for beams reinforced for shear and flexure with Sika products.

1 LAYER REINFORCED FOR FLEXURE:



Many flexural cracks appear. Beam fails in shear with local stresses causing the concrete to be disturbed at the ends of the beam. Pull-off of this concrete was also observed.

2 LAYER REINFORCED FOR FLEXURE:



Light flexural cracking. Local stresses cause cracking at the ends of the beam, but beam fails in shear.

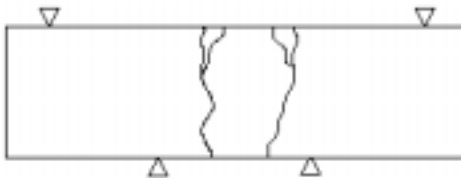
3 LAYER REINFORCED FOR FLEXURE:



Little or no flexural cracking. Cracks from local stresses at end of laminate develop, and beam fails in shear. Failure is due to local stress rather than shear, as shear cracking did not extend to the compression side on some beams.

Figure B.5.1.3: Typical cracking and failure modes for beams reinforced for flexure with Tyfo® carbon FRP.

1 Layer - flexure and shear:



Flexural cracking originating along edge of shear laminate. Eventual flexural failure of concrete and laminate. Local stresses at ends of flexural laminate not real apparent.

2 Layer - flexure and shear:



Flexural cracking starts very similar to one layer beams (along shear lam. edge). Eventually local stresses at ends of beam cause cracking at the end of the beam, and the beam shears.

3 Layer - flexure and shear:



Light flexural cracking. Debond of shear laminate. Local stresses cause cracking at end of beam. Failure caused by debond of shear laminate (Shaded Area).

Figure B.5.2.3: Typical crack patterns and failure modes for beams reinforced with Tyfo® carbon for flexure and shear.

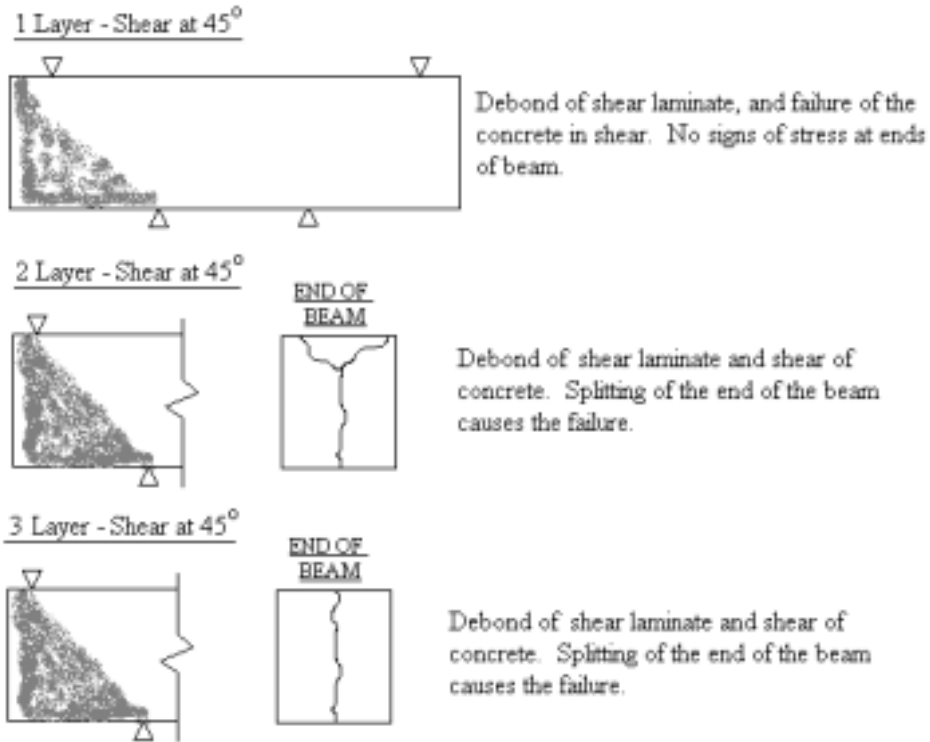


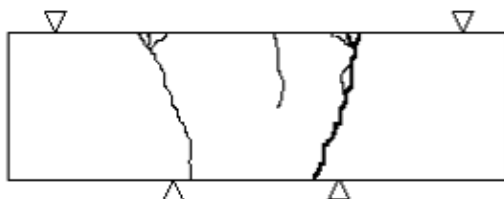
Figure B.5.3.4: Typical cracking and failure modes of beams reinforced with Tyfo® carbon for shear at 45°.

1 LAYER REINFORCED FOR FLEXURE:



Shear cracking occurs but the beam fails in flexure. The failure is within the middle third of the beam.

2 LAYER REINFORCED FOR FLEXURE:



Flexural cracking followed by flexural failure of the concrete and debonding of the laminate at ends of beam.

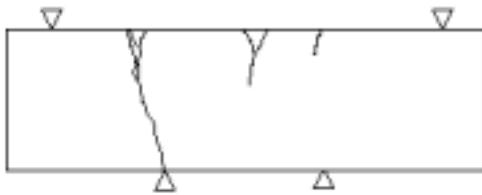
3 LAYER REINFORCED FOR FLEXURE:



Beam fails in shear with little presence of flexural cracking. Beam is clearly over reinforced.

Figure B.6.1.3: Typical failure modes for CMI/Reichhold beams reinforced for flexure.

1 LAYER REINFORCED FOR FLEXURE AND SHEAR AT 90 DEGREES



Shear cracks form but beam fails predominantly in flexure. Laminate is failed across tensile (top) face of beam.

2 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 90 DEGREES



Flexural failure occurs with the failure of the laminate in the middle third of the beam. Limited shear cracking is observed.

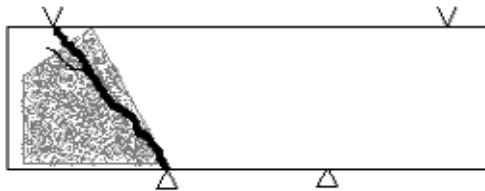
3 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 90 DEGREES



Flexural and shear cracks develop with the ultimate failure of the flexural laminate in the middle third of the beam.

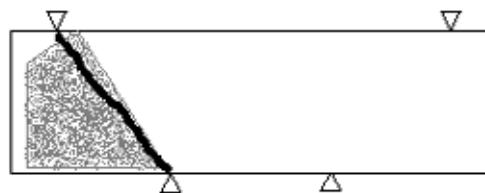
Figure B.6.2.3: Typical failure modes for CMI/Reichhold beams reinforced for flexure and shear at 90 degrees.

1 LAYER REINFORCED FOR FLEXURE AND SHEAR AT 45 DEGREES



Little flexural cracking is observed. Beam fails ultimately in shear with debonding of shear laminate and fracture of flexural laminate near the support. Some fracturing of shear laminate is observed but not typical.

2 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 45 DEGREES



Beam fails in shear with little presence of flexural cracking. Shear laminate debonds while flexural laminate fractures near the support.

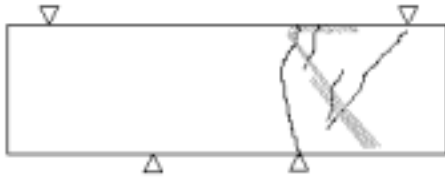
3 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 45 DEGREES



Beam fails in shear with little presence of flexural cracking. Shear laminate debonds while flexural laminate fractures near the support.

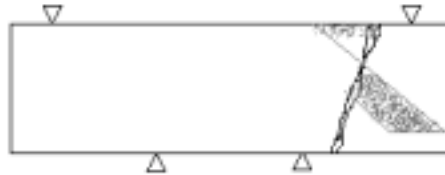
Figure B.6.3.3: Typical failure modes for CMI/Reichhold beams reinforced for flexure and shear at 45 degrees.

1 LAYER REINFORCED FOR SHEAR AT 45 DEGREES*



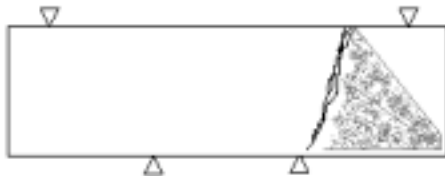
Flexural and shear cracking is observed. Shear laminate failure is indicated in grey. The flexural laminate fractures across the tensile face of the beam outside the middle third of the beam.

2 LAYERS REINFORCED FOR SHEAR AT 45 DEGREES*



Shear cracking causes debonding of the shear laminate. Flexural laminate is fractured across the tensile face outside the middle third of the beam.

3 LAYERS REINFORCED FOR SHEAR AT 45 DEGREES*



Shear laminate debonds while flexural laminate is fractured across the tensile face outside the middle third of the beam.

Figure B.6.4.2: Typical failure modes for CMI/Reichhold beams reinforced for shear at 45 degrees.

1 LAYER REINFORCED FOR FLEXURE:



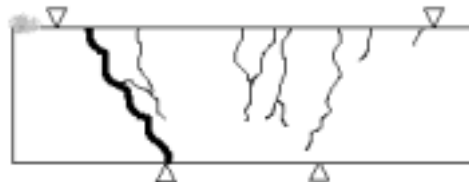
Many flexural cracks and few shear cracks. Beam eventually fails in flexure at or near loading points. Laminate is failed as well. No sign of debonding.

2 LAYER REINFORCED FOR FLEXURE



Clear flexural cracking with many shear cracks. Beam eventually fails in shear. Laminate does not fail.

3 LAYER REINFORCED FOR FLEXURE:



Many flexural cracks. Beam fails in flexure or flex/shear combined. Laminate debonds at end of beam (shaded area).

Figure B.7.1.3: Typical crack patterns and failure modes for beams reinforced for flexure with the MBrace™ glass system.

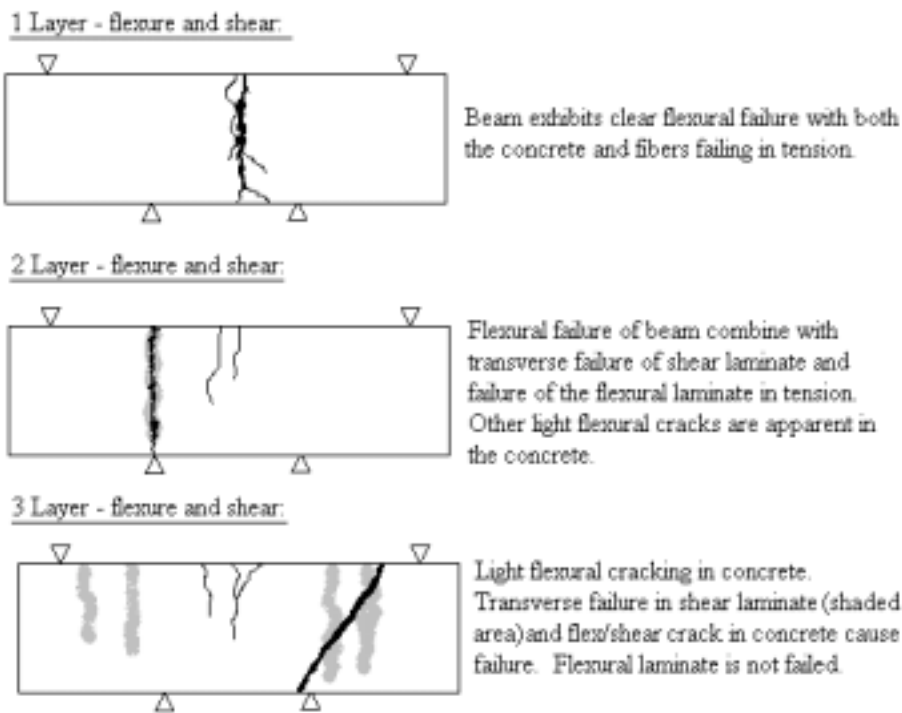


Figure B.7.2.3: Typical cracking and failure modes for beams strengthened with the MBrace™ glass system for shear and flexure.

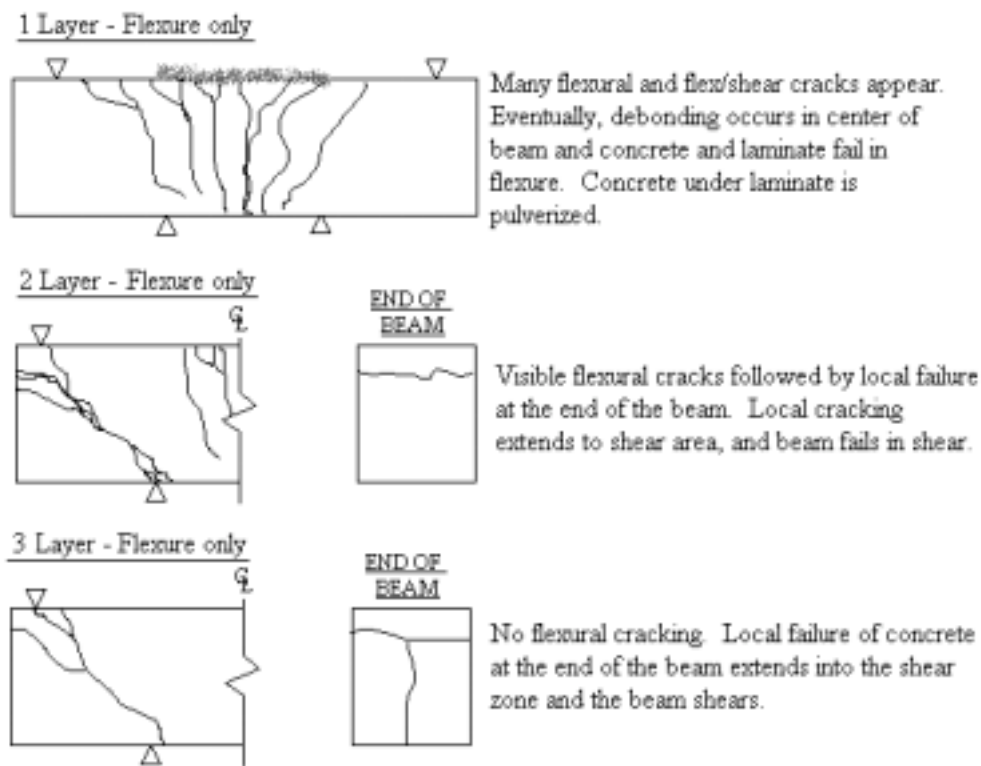
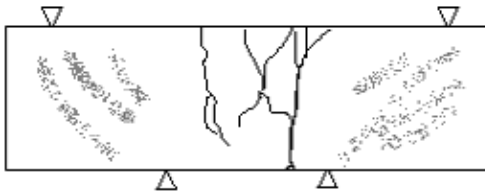


Figure B.8.1.3: Typical cracking and failure modes for beams reinforced with the Tyfo® glass system for flexure only.

1 Layer - flexure and shear:



Flexural cracking originating along edge of shear laminate. Eventual flexural failure of concrete and laminate. Visible cracking of resin over shear laminate (showing signs of stress in shear laminate - shaded area).

2 Layer - flexure and shear:



Obvious flexural cracking. Eventually shear laminate debonds (shaded area) and concrete fails in shear. Local cracking develops as it does with carbon at the ends of the beams.

3 Layer - flexure and shear:



Light flexural cracking. Debond of shear laminate. Local stresses cause cracking at end of beam. Failure caused by debond of shear laminate (shaded area) and shear cracking.

Figure B.8.2.3: Typical cracking and failure modes for beams reinforced with the Tyfo® glass system for flexure and shear.

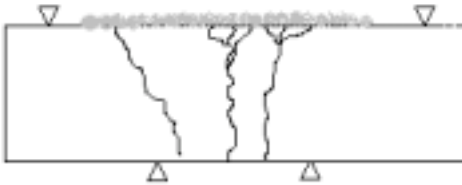
1 Layer, 2 layers, and 3 layers- Shear at 45°



Debond of shear laminate, and failure of the concrete in shear. No signs of stress at ends of beam.

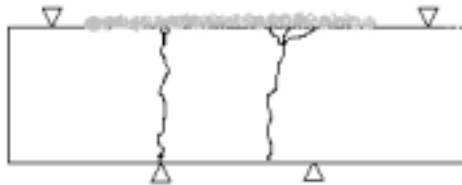
Figure B.8.3.4: Typical failure mode of beams strengthened with the Tyfo® glass system for shear at 45°.

1 LAYER REINFORCED FOR FLEXURE:



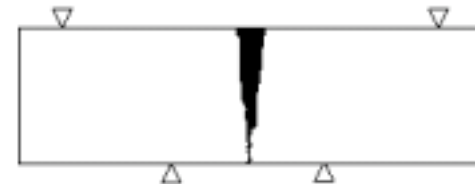
Flexural cracking and eventual failure of concrete. Laminate debonds in center of beam (shaded grey area), and laminate fails both parallel to and across the fibers.

1 LAYER REINFORCED FOR FLEXURE AND SHEAR:



Flexural cracking and failure with debonding of flexural laminate (grey area). Shear laminate fails in direction of long fibers (perpendicular to tension face). It should be noted that the flexural laminate is not completely failed.

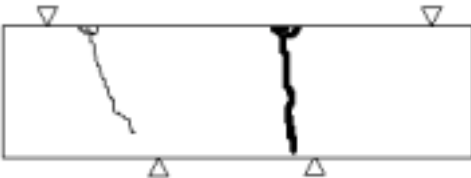
1 LAYER REINFORCED FOR SHEAR ONLY:



Flexural failure of beam combined with failure of the long fibers of the shear laminate. Beam does not fall apart, but crack widens (as much as 1/2") and load is not regained.

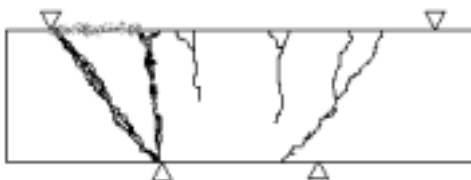
Figure B.9.3: Typical failure modes and cracking for beams reinforced with the Clark Schwebel Structural Grid.

1 LAYER REINFORCED FOR FLEXURE:



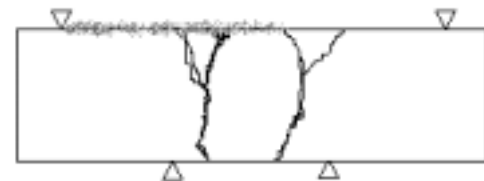
Some shear cracking occurs but the beam ultimately fails in flexure. Laminate fails and debonds across tension face above critical flexural crack. Failure is within the middle-third of the beam.

2 LAYER REINFORCED FOR FLEXURE:



Flexural cracks appear first followed by shear cracking. Beam eventually fails with critical cracking in both shear and flexure. Laminate fails across the tension face at the top of the shear crack. Debonding occurs at edge of laminate between shear and flexural cracks. (Shown in grey.)

3 LAYER REINFORCED FOR FLEXURE:



Beam fails in flexure with little presence of shear cracking. Laminate does not fail completely across tension face. Debonding occurs over approximately one-third of the width and one-half the length of the tension face.

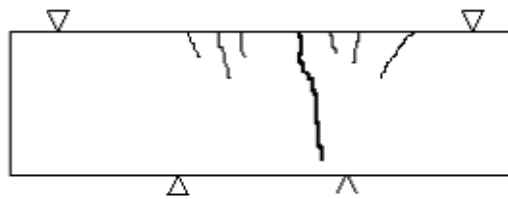
Figure B.10.1.3: Typical failure modes for beams reinforced for flexure with Owens Corning/Reichhold.

1 LAYER REINFORCED FOR FLEXURE AND SHEAR AT 90 DEGREES



Flexural cracking is observed followed by flexural failure in middle third of beam. Flexural laminate fractures across tensile face of the beam.

2 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 90 DEGREES



Some shear cracking occurs followed by flexural failure in the middle third of the beam. Flexural laminate fractures across tensile face of the beam.

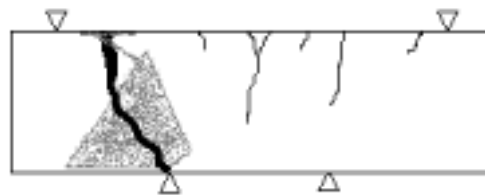
3 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 90 DEGREES



Beam exhibits substantial shear and flexural cracking. Beam fails in combined flexure and shear. Flexural laminate fractures across tensile face outside the middle third of the beam.

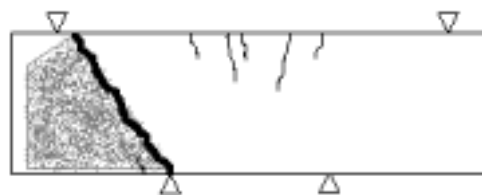
Figure B.10.2.3: Typical failure modes for Owens Corning/Reichhold beams reinforced for flexure plus shear at 90 degrees.

1 LAYER REINFORCED FOR FLEXURE AND SHEAR AT 45 DEGREES



Flexural and shear cracking is observed. Beam fails in a combined flexural/shear mode. Some of the shear laminate is fractured while the majority debonds. Flexural laminate fractures outside the middle third of the beam.

2 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 45 DEGREES



Flexural cracks form but beam fails in shear followed by debonding of the shear laminate. Flexural laminate fails near the support.

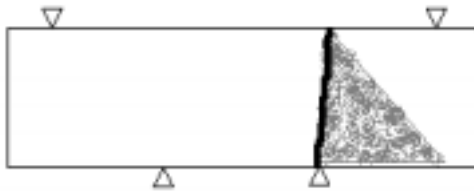
3 LAYERS REINFORCED FOR FLEXURE AND SHEAR AT 45 DEGREES



Flexural cracking is observed but ultimate failure is in shear. Shear laminate debonds followed by fracture of flexural laminate near the support.

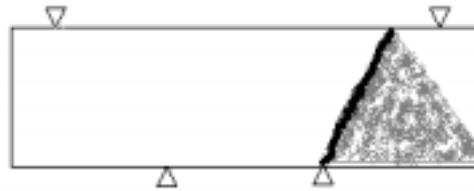
Figure B.10.3.3: Typical failure modes for Owens Corning/Reichhold beams reinforced for flexure and shear at 45 degrees.

1 LAYER REINFORCED FOR SHEAR AT 45 DEGREES*



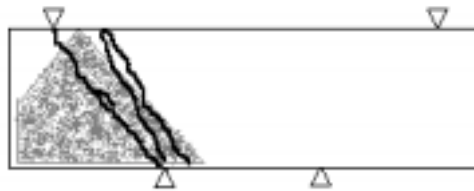
Flexural cracking in the middle third of the beam is not observed. Shear laminate debonds while the flexural laminate fractures across the tensile face just outside the middle third of the beam.

2 LAYERS REINFORCED FOR SHEAR AT 45 DEGREES*



Flexural cracking in the middle third of the beam is not observed. Major cracks are angled toward the support but fall intermediate to a pure flexural or shear crack. Shear laminate debonds while the flexural laminate fractures between the load point and the support.

3 LAYERS REINFORCED FOR SHEAR AT 45 DEGREES*



Shear cracking occurs along with some cracking that is skewed vertically. Shear laminate debonds while the flexural laminate fails near the support.

Figure B.10.4.2: Typical failure modes for Owens Corning/Reichhold beams reinforced for shear at 45 degrees.