Evaluation of Crack Control Methods for Deep Pretensioned Bridge Girder Ends

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Pretensioned bridge girder end cracks have been a concern for girder manufacturers and designers. The cracking appears to be more severe in recently developed deeper sections with slender webs and with larger amounts of prestress. While some smaller cracks are considered to be acceptable and can be sealed, girders with larger cracks pose durability concerns. The cracks close to strands could be particularly harmful if corrosion agents reach strands. In Wisconsin cracked girders are of concern to the Department of Transportation, but in some states they are used to reject girders[1].

The girder end cracks are not random and exhibit characteristic patterns. Figure 1 shows the types of cracks studied in this paper on a 54in deep bulb tee girder, studied in this paper. They are classified as horizontal web cracks (widths of 0.004-0.010in.), inclined cracks (similar widths to web cracks), and the bottom flange Y cracks (up to 0.06in.). Multiple horizontal cracks occur in the web due to the eccentricity of the strands over the depth of the girder. The inclined cracks form closer to the top flange, around the draped strands. These are often the longest cracks and are triggered by tensile strains created by the draped strands. The horizontal web cracks and inclined cracks are expected to close under service loading. Surveys of bridge engineers show that these cracks are generally thought to be induced by the strand distribution in the girder or the detensioning procedures and repair procedures are suggested[1].

The Y or T shaped cracks form at the intersection of the web and the bottom flange, and propagate down through the bottom flange. These cracks are close to the bottom flange strands and could form paths for corrosion agents to reach the strands. They are not expected to be closed with the service loads but may be constrained if cast-in-place end diaphragms are used. Vertical transverse cracks across the bottom flanges, reported by other researchers[2, 3], are out of the scope of this study since no such cracks form in the girders examined by the authors.

The crack control method most commonly used and investigated by previous researchers involves adjustments to the end zone reinforcement pattern[4-7]. Recommendations on the design of the end zone reinforcement area and the spacing were developed based on experimental or linear analytical studies. Kannel et al.[3] investigated debonding strands and changing the strand cutting order to control cracking using linear finite element analysis (FEA). Their research focused on entirely different types of cracks: cracking at the base of the web, and inclined and vertical cracks on the sides of the bottom flange. Burgueno and Sun[8] studied strand debonding through nonlinear FEA but only considered the localized damage around the strands.

This research investigated the impact of crack control methods on the tensile strains which cause characteristic cracks at the girder end. The relative reduction in tensile strains achieved by each crack control method, related to each type of crack, is reported. The pretensioned girder end zones were analyzed by FEA after the method was verified by comparison with test data. The accuracy of the FEA is achieved by incorporating the nonlinear properties of concrete and the redistribution of strains after cracking into the material model. A quantitative evaluation of the strain reduction over the entire girder end zone due to the use of crack control methods does not exist in the literature but is provided in this paper.

The crack control methods investigated in this paper included varying the order in which the strands were cut, changing the draped strand pattern, modifying the end zone reinforcement pattern, debonding strands, and changing the location of the lifting hoops.

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The Standard Girder

The impact of the crack control methods were investigated on a 54in deep wide flanged bulb Tee girder that was taken as a standard basis for comparison. This 129ft long girder design was taken from a real bridge. The girder was examined for cracks right after fabrication and exhibited all three types of cracks. The girder had 32 straight and 8 draped strands. Strands were 0.6in diameter 270ksi low relaxation type. The total initial prestressing force applied on the strands was 1758kips, or 44kips for each strand. The slope of the center line of the draped strands was 8%. The strands were de-tensioned by flame cutting, starting with the draped strands and continuing with the bottom row straight strands, the upper row of straight strands and finally the middle row of the straight strands. The exterior strand of each row was cut first, moving to the interior.

The strand pattern and the end reinforcement details are shown in Figure 2. The strength of the concrete measured through cylinder tests right before transfer was 6974psi. The rebar nominal yield strength was 60 ksi.

This girder was modified by the various methods noted and the effectiveness for crack control was evaluated by comparing the results to the standard girder.

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The Finite Element Modeling

The finite element analysis (FEA) software ABAQUS[9] was utilized to simulate the girder end behavior. Nonlinear FEA of concrete involving cracking can take considerable computation time and space. For computational efficiency, only a quarter of the full girder was modeled utilizing symmetry along the girder length and width.

A “concrete damaged plasticity” model of ABAQUS was utilized. This model is suitable for simulating the nonlinear behavior of concrete in compression and tension under monotonic loading. The material properties defined by the FIB Model Code 2010[10] were used for the plastic range of the stress strain relationship for concrete in compression and for the stress-crack opening relationship of concrete in tension. For the behavior when the concrete strains are elastic and linear, the modulus of elasticity given by the AASTHO LRFD Bridge Design Specifications[11] was judged to be a good representation and used. In order to reduce the computation time, only the region of interest, within a distance equal to the girders depth from the end was modeled with nonlinear concrete material. The reinforcement bars were modeled as linear elastic with the modulus of elasticity given by the AASHTO LRFD specifications.

The rebar elements were embedded among concrete elements. The material model for concrete as described allows the concrete elements to lose stiffness when they reach their cracking strain and the stresses to be redistributed to the rebar elements. The bond between the rebars and concrete was implicitly simulated by assigning an added ductility to concrete, provided by the rebars, during the tension softening stage.

Since the scope was to investigate the cracks forming soon after the prestress release, the only loading applied on the girder was the prestressing force. The initial prestressing force was applied on the concrete by excluding the strands from the model and applying a surface stress to the concrete along the strand surface over the transfer length. The transfer length was taken as 60 times the strand diameter and the bond stresses were assumed to be uniform per AASHTO LRFD specifications.

The three dimensional model was meshed densely at the girder end, where the stress accuracy was important. The mesh size was gradually increased away from the girder end. The concrete elements in the nonlinear region, concrete elements in the linear region and the rebar elements were discretized with 4 node tetrahedral, 6 node triangular prism and 2 node truss elements, respectively.

The FEA predicted the crack locations observed in the field well. The techniques and material properties were also verified using available test data. A satisfactory correlation was achieved for the strains measured through tests and the FEA of the girder tested. Additional details on material properties, modeling techniques and model verification can be found elsewhere[12].

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The Evaluation of Crack Control Methods

The effectiveness of the crack control methods was investigated by incorporating them into the FEA and comparing the results with behavior of the standard girder described in the previous section. Principal tensile strains in the concrete are the best indicators of cracking with the concrete damaged plasticity model of ABAQUS. The reduction in principal tensile strains due to crack control methods, in comparison to the standard girder, was found to be the most suitable method of assessing the impact of the controls.

The theoretical cracking strain of concrete was calculated assuming a linearly proportional stress strain relationship for concrete in tension up to cracking. AASHTO LRFD Bridge design specifications, section C5.4.2.7 and 5.2.4.2 were used to calculate the cracking strength and the modulus of elasticity. The cracking strength for the 7000 psi concrete used in this study was calculated to be 124 microstrains (με). Principal tensile strains over this value in the FEA results indicate cracking.

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Tensile Strains in the Standard Girder End

A contour plot of the principal tensile strains near the end of the standard girder from the FEA is given in Figure 3. The regions where the tensile strains peak correlate well with the locations of inclined, horizontal web and Y cracking. Darker colors indicate low strains and the magnitudes of the highest strains are marked at selected regions.

The following modifications were implemented to the standard model to assess their contributions in crack control. The results of the following FEA use the same contour plot legend with the same intervals as in Figure 3 unless indicated otherwise.

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Strand Cutting Order

The prestressing load generally is transferred to the girder in steps, in most cases by flame cutting one or two strands at a time. Since the girder end regions exhibit nonlinear behavior, the order in which the strands are cut could have an impact on the resultant strains. The web cracks and Y cracks in the standard girder are a result of the eccentricity of the strands along the girder depth and the girder width, respectively. Therefore, different strand cutting patterns will change the eccentricity of the load at any step.

The strand cutting patterns studied are shown in Figure 4 where the strands are replaced by numbers each denoting the step in which each strand is cut. On the left, a case is shown where the bottom strands were released starting with the most exterior strands having the largest eccentricities across the width. This case was compared to one where the opposite was practiced by releasing the most interior strands first, as shown on the right. All models created use symmetry. Therefore, the FEA simulates cases where the strands were cut simultaneously on both sides of the flange.

Figure 5 compares the magnitudes of the principal strains for the two models on the symmetric half of the bottom flange at the very girder end where the Y cracking occurs. The principal tensile strains perpendicular to expected Y cracks are higher for the case where the exterior strands are cut first. It can be concluded that cutting the interior strands first and going towards the exterior would not eliminate Y cracking but could reduce the crack size. Therefore, it is recommended that the strand cutting should start from the interior strands and move outward where possible.

Changing the strand cutting order in the vertical direction resulted in insignificant differences in the results. This finding is attributed to insignificant variation of the individual strand eccentricity in the direction of the girder depth compared to the girder depth.

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Modifications to Draped Strands

<subhead 3> **Removing the Draped Strands**

The standard girder used 8 draped strands to limit the tensile stresses on top of the girder. The FEA of a girder with the same number of straight strands but with no draped strands does not meet the requirement for top fiber tension limit but was created to isolate the contribution of draped strands to end cracking. Figure 6 shows the principal tensile strains for the girder end without draped strands for comparison to the strains of the standard girder with draped strands in Figure 3.

Even though tensile strains perpendicular to the inclined cracking direction remained without the draped strands, these strains were considerably lower. Girders without draped strands, therefore, are not expected to form visible inclined cracks. Draped strands trigger inclined cracks by forming tensile strains perpendicular to their direction while transferring compression to the girder.

Draped strands create an internal moment in the web in opposition to effects of the bottom flange strands. Therefore, removing the draped strands from the model also decreased the web strains causing web cracking. The web still cracks, however, with strains remaining well above the cracking limit, 124με.

<subhead 3> **Lowering the Draped Strands**

Girder manufacturers reported observing less severe cracking in girders where the center line of the draped strands was lower in height. This trend likely is a result of the fact that the girders where the draped strands need not be high are also girders with fewer total strands.

A model of a girder where the center line of the draped strands is located only 31in from the bottom of the girder at the end, but identical to the standard girder in other features, was created. The principal tensile strains with the lower draped strands are shown in Figure 7.

When compared to the principal tensile strains of the standard girder in Figure 3, it can be concluded that lowering the draped strands lowers the location of the inclined crack but does not significantly reduce the strains causing inclined cracking.

Lower draped strands have smaller eccentricities along the depth and therefore cause just slightly smaller horizontal web cracking strains. The area where the horizontal web cracks occur is constrained between the draped strands and the bottom flange strains and therefore is smaller.

It should be noted that the draped strands work to cancel the tensile stresses at the top fiber and are the most efficient when located closer to the top. Moving the draped strands down, would normally be accompanied by reducing the number of straight strands (if the end stresses control rather than stresses at hold down points) making the girder less efficient in load capacity or span length.

<subhead 3> **Lowering and Spreading Out the Draped Strands**

Draped strands are typically spaced at 2in center to center spacing. This causes the concrete stresses transferred by the draped strands to be rather concentrated. An alternative is to spread the draped strands along the girder web allowing the force to spread over a larger area. This also requires the center line of the draped strands to move lower in the web. The girder where the drape strands were lowered to 31in from the bottom with 2in spacing presented in the previous section was compared to a model with a girder with 8in strand spacing. The centroid of all the draped strands was at the same height. A contour plot of principal concrete tensile strains for this case is shown in Figure 8. The reduction in tensile strains associated with inclined cracks due to spreading of the draped strands can be seen by comparing Figure 7 to Figure 8.

Fanning out the draped strands is effective in eliminating or reducing the size of inclined cracks. This solution also requires lowering the draped strands, and again may limit the number of straight strands and the girder's moment capacity.

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Modifications to the End Zone Reinforcement

AASHTO LRFD Bridge Design Specifications require vertical bars to be designed to prevent "splitting" with web cracks and confinement reinforcement around the strands against "bursting". The standard girder examined in this study experienced splitting (web cracks) and bursting (the Y crack) cracks despite satisfying both requirements.

The ends of these girders, with thin webs and curved web and flange junctions, are congested areas. Therefore increasing the reinforcement by increasing the size or number of bars present is judged to be an impractical solution. Nevertheless, a girder with increased vertical rebar size was studied to illustrate the effectiveness of those bars in controlling web cracking and the potential strain reduction they could provide.

The standard girder had 5 pairs of #6 stirrups at the girder end spaced at 3 in as shown in Figure 2. The splitting reinforcement was designed according to AASHTO LRFD Specifications. Namely, this steel area corresponds to a rebar resistance of 4% P_i within h/4 from the girder end, where P_i is the total prestressing force at transfer, h is the girder depth. For comparison with the standard case, FEA studied three alternate girders where: 1) these stirrups were replaced by #10 bars, with a resistance of 12% P_i in h/4 (5 #10 @ 3in), 2) only the first two pairs of #6 bars from the end were replaced by #10 bars, resisting 6% P_i in h/4 (2 #10 @ 3in), 3) the #6 bars were spaced at 1.8in, resisting 7% P_i in h/4 (5 #6 @1.8in). The principal web tensile strains with varying rebar designs are plotted over the depth of the girder in Figure 9. Figure 9 on the left shows the strains at the girder end (crossing the web cracks) and Figure 9 on the right shows strains at 16.5in away from the girder end (crossing the inclined crack). The theoretical cracking strain limit is also shown on the plots.

The comparison in Figure 9 on the left side shows that even though #10 bars decrease the principal tensile strains causing web cracking by up to 50%, the strains remain well above the cracking limit. Though smaller cracks could be expected, even with an unrealistically large sized #10 bar, it is not possible to eliminate cracking completely.

The results with 5 pairs of #10 rebars and only 2 pairs of #10 rebars were nearly identical in reducing the size of web cracks in Figure 9. The strains reduced to below the cracking limit after 18in from the girder end and therefore increasing the reinforcement area after this distance did not change the results of the FEA. This finding verifies the recommendations of the earlier researchers[4] for placing most of the rebars closer to the end.

Unlike the web cracks, the inclined cracks and the principal tensile strains do not form perpendicular to the reinforcement bars. The reduction in tensile strains for the inclined cracks shown in Figure 9 on the right side was limited to 24% and not significant. The strains remained well above the cracking limit with all reinforcement patterns.

Increasing the confinement reinforcement area also did not reduce the strains causing the Y cracks significantly. This might be because the Y crack formation starts at the very end of the girder and the tension strains are not completely parallel to the confinement reinforcement.

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Debonding Strands in the End Zone

Debonding some of the strands at the girder end will decrease the stresses transferred to concrete, and consequently should reduce the tensile strains causing cracking. To investigate the level of debonding required to limit or eliminate cracking, FEA of girders where 25%, 35% and 50% of the strands were debonded were compared to the standard girder. The strand debonding was terminated in three steps at 15, 25 and 35ft into the girder. It may be preferable to use shorter debonded lengths to avoid dynamic loading when strands are detensioned by cutting rather than gradual release. Figure 10 shows the pattern of strands which remain bonded at the girder end. Debonding some strands at the girder end reduces or eliminates the need for the draped strands. The FEA assumed rigid sleeves for debonded strands, and therefore there was no stress transfer assumed in the debonded region.

Figure 11 shows the principal tensile strain contour plots of the girder end for cases where 25%, 35% and 50% of the strands are debonded. Limiting the web cracking strains entirely below the cracking limit was only possible with 50% debonding. On the other hand, 25% and 35% debonding reduced the strains considerably and will likely limit the number of cracks and sizes.

The strains in the inclined cracking region were below the cracking limit for all cases. Inclined cracks are associated with the tensile strains created by the draped strands. As the need for draped strands is reduced with debonding, no inclined cracks are expected in girders with debonding.

The Y cracking strains were eliminated with as low as 25% debonding. This was only possible if the strand pattern to remain bonded is selected so that the inner most strands remain bonded and the rest of the strands are distributed uniformly along the bottom flange. Strand patterns shown in Figure 10 are arrangements selected to eliminate Y cracks.

This finding on the Y cracking is in agreement with the earlier findings on strand cutting order. The presence of the compression force in the middle of the flange, due to the interior strands, has a constraining role on the bottom flange strains. In absence of this compression force, Y cracks are more likely to occur.

The locations where the debonded strands are bonded to concrete did not exhibit any plastic strains, when the strands were bonded in stages per AASHTO LRFD requirements.

<Subhead 3>

Debonding all strands for 12in

FEA of the selected girder was also modified to simulate a case where none of the strands of the standard girder were bonded until 12in into the girder. Shifting the prestress transfer 12in into the girder provides more concrete volume to resist the cracks which normally initiate at the girder end: the horizontal web cracks and Y cracks.

Figure 12 compares the strains along the height crossing the web cracks of the standard girder to that of the girder where strands are not bonded until 12in away from the end. To serve as a point of reference, the case with 35% debonding (65% bonded strands) is also included.

Figure 12 shows that bonding strands 12in away from the girder end results in significant reduction of the tensile strains in the web area, comparable to a case where 35% of the strands were debonded over a 15ft length. It also decreases the Y cracking strains below cracking magnitudes. The tensile strains in the inclined cracking region, not shown in the figures, were only improved slightly by this change compared to the standard case.

Debonding all strands for a short distance from the girder end is an effective means of controlling end cracking, other than inclined cracks. Having no strands bonded for 12in from the girder end is not expected to affect the shear capacity of the girder since this area is in most cases enclosed in a diaphragm beam.

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Lifting the Girder

The cracks that form during prestress release have been observed to widen considerably when the girder is lifted from the casting bed. The girders are lifted from each end by embedded lifting loops in the concrete. The lifting loops are typically in the top flange and placed at a distance equal to the girder depth from the end. This case was simulated by removing the simple support at the bottom of the girder at the end, and supporting the girder through the lifting loop locations while under gravity loads.

Figure 13 shows the amplified principal tensile strains on a contour plot due to lifting at 54in form the end. Web cracking strains closer to the bottom flange were amplified by a factor of 2.2. The inclined cracking strains increased significantly after lifting by a factor of 2.4. The Y cracking strains decreased by the removal of the support at the girder bottom, however this decrease was not significant.

The impact on the principal tensile strains in the inclined cracking region from placing the lifting hoops closer, at 36in, and further, at 108in, from the girder end is shown in Figure 14. Lifting the girder further away, at 108in from the end, increases the strains in the end region as the cantilevering portion of the girder is longer. On the other hand, lifting it from a location within the nonlinear region, at 36in, also causes high tensile strains inducing additional cracking shown by the second peak on Figure 14. The girders should be picked up as close to the end as possible without getting into the nonlinear region. The practice of lifting the girders at a distance equal to the girder depth was found to be the best practice.

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Summary

The impact of various methods for controlling cracks that form at ends of deep pretensioned girders, after prestress release, has been identified using nonlinear FEA. Principal tensile strains, the indicator for cracks when values exceed the cracking strain, were compared to strains in a standard Wisconsin girder with no enhancements for crack control.

Table 1 rates the impact of each control method on each type of crack examined. Debonding all strands for a short distance from the girder end, or debonding some strands for different distances along the length of the girder are the most effective solutions for crack control. The capacity of the girders with debonding, especially under shear, should be carefully checked when this method is employed. The AASHTO limits for number of strands debonded are often exceeded by various States as they were here. A combination of multiple methods could be used to further reduce strains.

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Conclusions and Recommendations

The "Y cracks", vertical cracks that form from the center of the girder bottom flange and extend upward until coupling with inclined cracks that intersect the web-flange joint, were judged as the most serious cracks that need to be controlled at the ends of bridge girders. These cracks intersect or occur alongside the bottom strands and can lead to strand corrosion and loss of girder strength, particularly if the girder ends are not embedded in a cast diaphragm. Since the cracks are in the girder bearing region, where moisture and de-icing salts are frequently present, the corrosion potential can be serious. Indications are that these crack openings can grow as the bearing forces on the flange increase, particularly if the end of the girder is not restrained by a cast-in-place concrete diaphragm.

Horizontal web cracks and the inclined cracks along draped strands may be less serious since they are expected to at least partially close as increased load is applied to the girders. Yet serious corrosion has been found in older girders along the draped strands. While the inclined cracks may still allow corrosive compounds to reach the draped strands, the horizontal web cracks are not likely to have an impact on strand corrosion.

Recommendations for controlling girder end cracks are provided in the following, starting with measures that may be the easiest to implement.

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Girder Lifting Points:

Lifting of the girder after the prestress release was found to increase the strains causing certain cracks and increase crack widths. This FEM finding matches well with the observed increase in crack openings during lifting of girders from casting beds. Lifting the girders right at the ends of the nonlinear zone, after a distance equal to the girder depth from the end, was found to be the best location to reduce crack widths.

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Strand Detensioning Sequence:

Changing the strand cutting order was not sufficient to eliminate Y cracking strains in the bottom flange. It can, however, reduce the width of the cracks. Since this method does not require any design changes, following a strand cutting sequence that starts with the most interior strands and move towards the exterior ones is recommended where practical.

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Changing Draped Strands

The inclined cracks are triggered primarily by the draped strands. Draped strands could be eliminated, but bottom strands may also have to be reduced to control top flange stresses when large numbers of straight strands are used. The girder's load capacity would also be reduced. Girders without draped strands are very unlikely to develop inclined cracks.

Lowering the draped strands is not found to control inclined or web cracks very well.

Lowering and spreading the draped strands is effective in keeping the inclined cracking strains below the cracking limit but does not eliminate web cracking or affect bottom flange Y cracking. Since moving the draped strands lower also may reduce the number of straight strands that can be used in the bottom flange, this method may be inefficient for heavily prestressed girders and is not recommended in those cases since it decreases girder capacity.

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Providing Additional Web Reinforcing:

Increasing the vertical reinforcement area in the end zone alone is not recommended because it is not sufficient to eliminate cracking, though it does help control crack widths. Even when the standard reinforcement area was tripled, the concrete strains were still well above the cracking limit. As the room in the girder webs is already constrained, it is not practical to place larger or more bars in this area.

The first two sets of bars closest to the girder end were determined to be the most effective bars in controlling web crack size. Adding additional bars further into the section is not useful in controlling web cracks.

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Strand debonding:

Debonding strands at the girder ends is a highly recommended solution for all types of cracks, but particularly for the more critical Y cracks.

The pattern of strands to remain bonded at the end should be selected so that the most interior strands of the bottom flange are fully bonded, and the rest of the bonded strands are evenly distributed across the bottom flange.

25% debonding was adequate to eliminate Y cracking and inclined cracking in a girder with a full complement of bottom strands. The complete elimination of web cracks requires 50% debonding, higher than the AASHTO limit, and is only recommended if the shear capacity of the girder can be assured to be sufficient.

Debonding all of the strands for a distance of 12in. into the girder is also highly recommended to control the web cracking and Y cracking. This should lead to fewer web and smaller web cracks and the elimination of the bottom flange Y cracks and therefore effectively the danger of bottom flange strand corrosion. Since the debonding is over a distance equal to common bearing lengths, the effect on shear capacity may not be serious but should be checked.

Even when debonding is used it is wise to follow the strand detensioning sequence recommended above to further control possible crack development.

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Abstract

Deep pretensioned concrete bulb Tee girders exhibit cracking at the end regions during detensioning. These cracks, discourage engineers from using deep sections, or if considered severe may result in the rejection of the girders upon shipment from a producer. The durability of the members is of concern, particularly if corrosion agents reach strands through cracks.

The industry uses various crack control methods chosen based on practical experience. The impact of these methods on controlling cracks has not been well quantified or compared. This paper describes an evaluation of the effectiveness of existing and proposed crack control methods. The girder ends were analyzed using nonlinear finite element analysis verified by test data. The effects of end zone reinforcement pattern, debonding of strands, strand cutting order, draped strand pattern, and lifting of the girder on cracks were examined. For each method, the reduction in the tensile strains associated with cracking is presented.

Keywords: end cracks; control; debonding, reinforcement, lifting, cutting order

Figure Captions

Figure 1 – Typical cracking pattern and crack types.

Figure 2 – The strand and reinforcement pattern at the girder end.

Figure 3 – Principal tensile strain contours for the standard girder.

Figure 4 – Strand cutting orders.

Figure 5 – Principal tensile strains with varying strand cutting sequence.

Figure 6 – Principal tensile strains with no draped strands.

Figure 7 - Principal tensile strains with lowered draped strands.

Figure 8 - Principal tensile strains with lowered and spread out draped strands.

Figure 9 – Principal tensile strains with varying reinforcement.

Figure 10 - The pattern of strands bonded at the girder end.

Figure 11 - Principal tensile strains with various levels of debonding.

Figure 12 – Principal tensile strains along the girder depth with debonding.

Figure 13 – Principal tensile strains after the girder is lifted at 54in from the end.

Figure 14 - Amplification of principal tensile strains with varying lifting locations.

Tables

Table 1 – The effectiveness of crack control methods.

Control Method		**Inclined Cracks**	**Web Cracks**	**Y Cracks**
Increase in ~~End Zone~~ Reinforcement Area of	The closest two bars	MILD	MODERATE	NONE
	Bars further away	NONE	NONE	NONE
	Bottom flange stirrups	NONE	NONE	NONE
Debonding Some Strands at the End		HIGH	MODERATE	HIGH
Debonding All Strands for 12in from the End		MILD	HIGH	HIGH
~~End Zone~~ Increase in Reinforcement Area& Debonding		HIGH	HIGH	HIGH
Change in Strand Cutting Order		NONE	NONE	MODERATE
Draped Strands	Removed	HIGH	NONE	NONE
	Lowered	NONE	MODERATE	NONE
	Lowered & Spread	HIGH	MODERATE	NONE

HIGH = can eliminate cracking

MILD = can reduce strains

MODERATE = can reduce strains significantly

NONE = has negligible impact

Figures

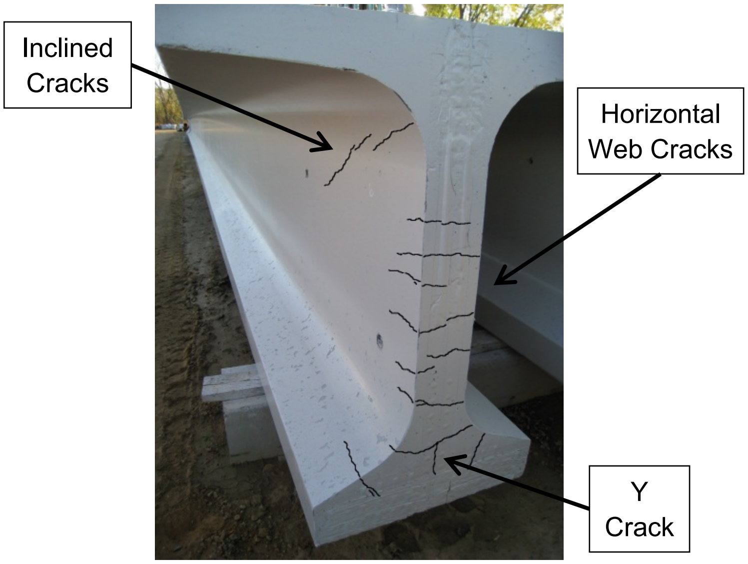
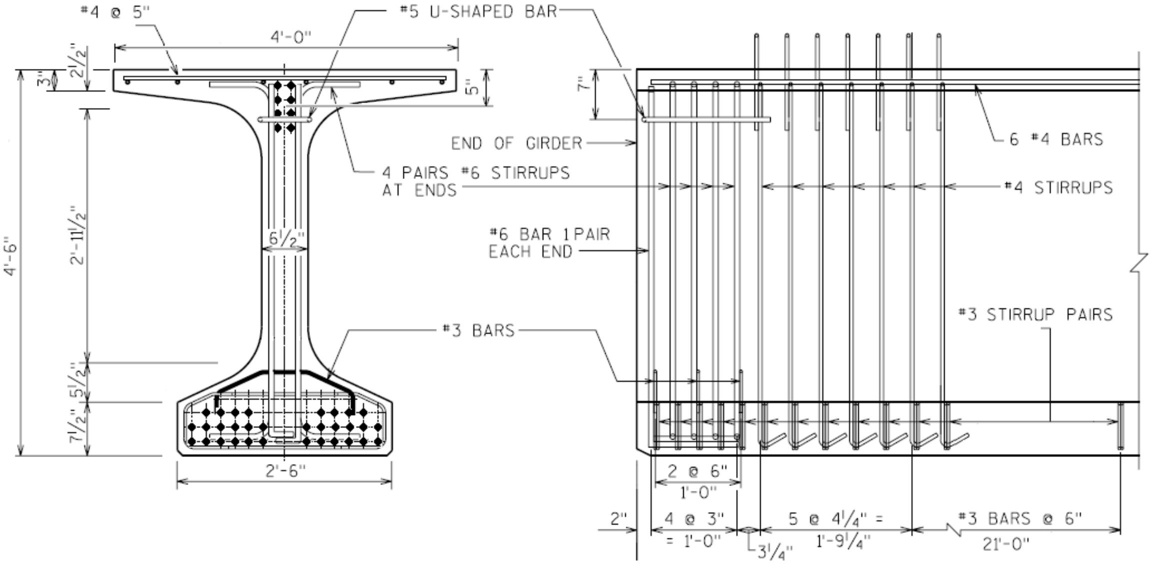


Figure 1 – Typical cracking pattern and crack types.



Cross Section at the Girder End

Elevation View
(strands not shown)

Figure 2 – The strand and reinforcement pattern at the girder end.

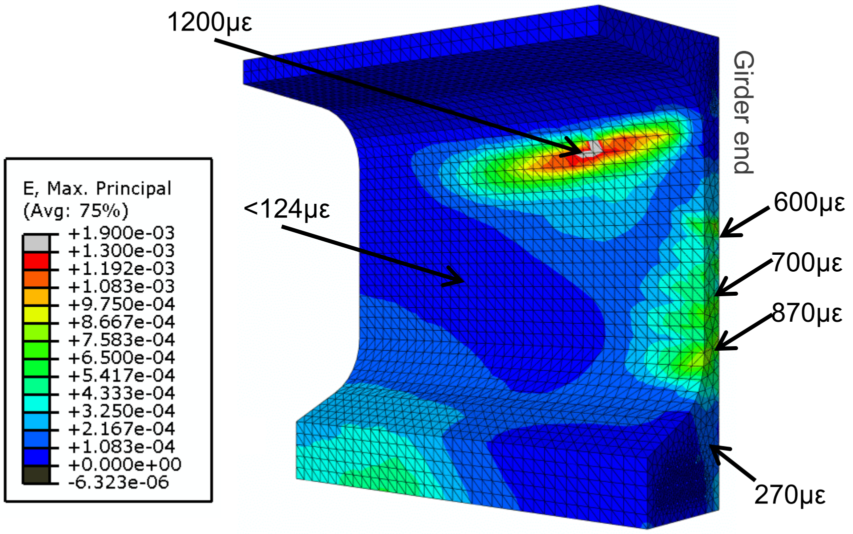
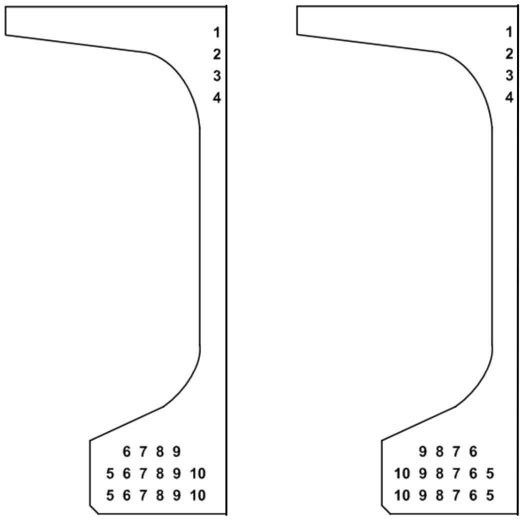
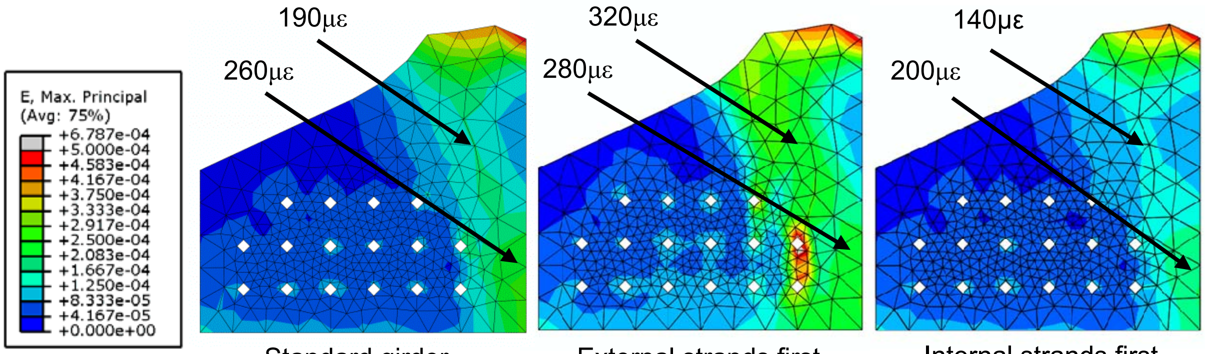


Figure 3 – Principal tensile strain contours for the standard girder.



External strands first Internal strands first

Figure 4 – Strand cutting orders.



Standard girder External strands first Internal strands first

Figure 5 – Principal tensile strains with varying strand cutting sequence.

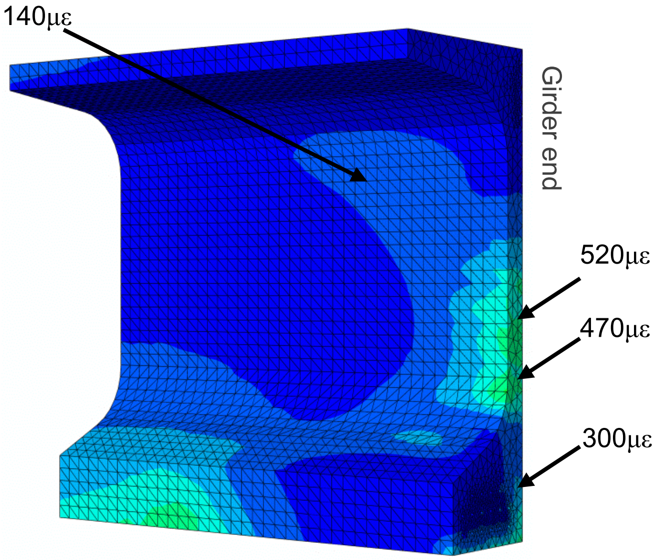


Figure 6 – Principal tensile strains with no draped strands.

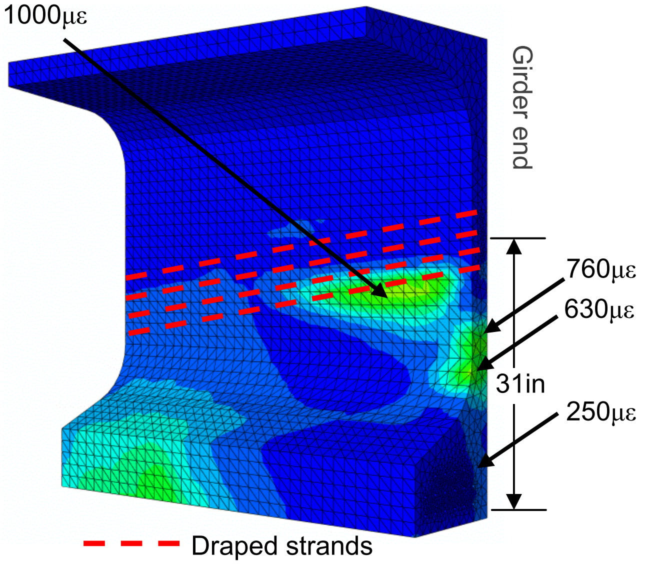


Figure 7 - Principal tensile strains with lowered draped strands.

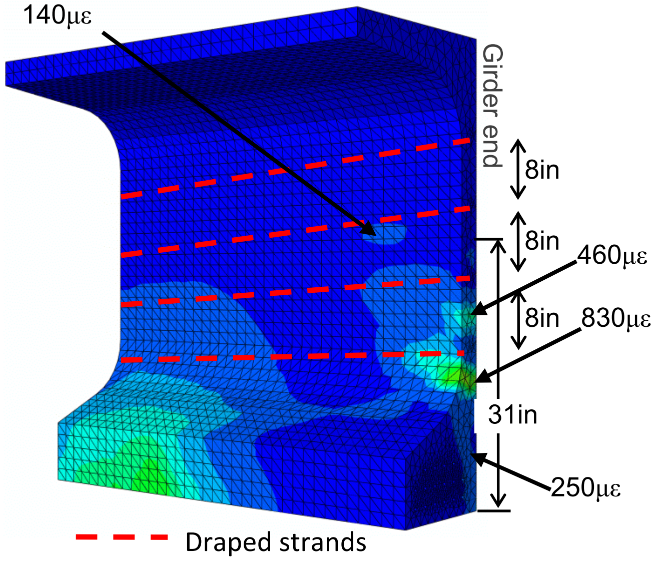


Figure 8 - Principal tensile strains with lowered and spread out draped strands.

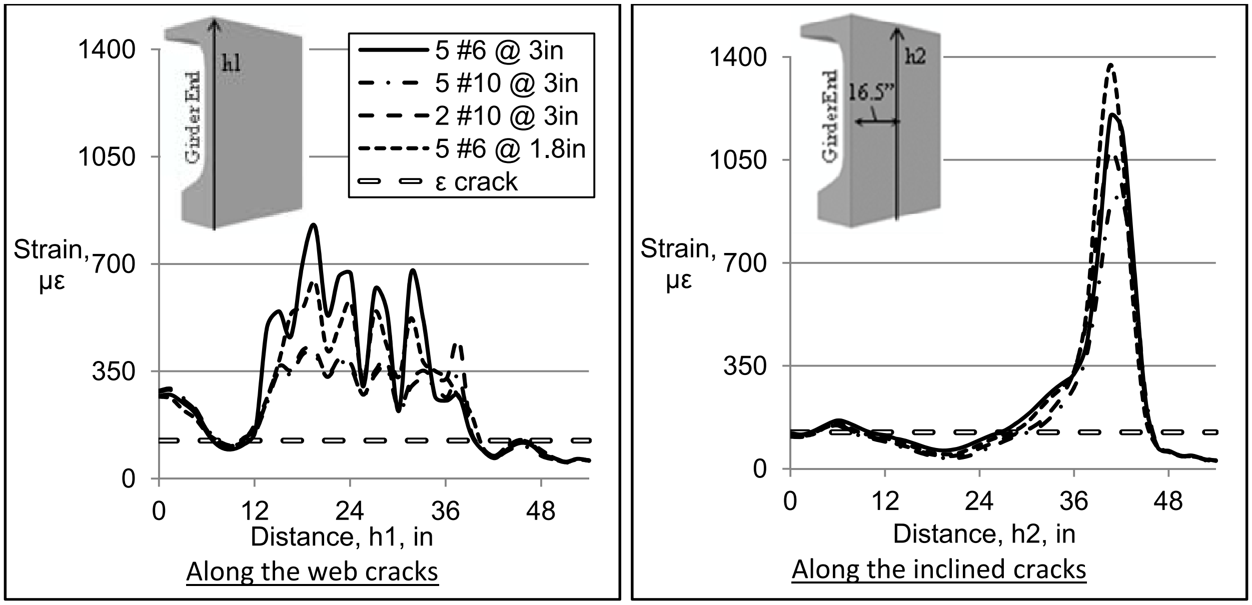


Figure 9 – Principal tensile strains with varying reinforcement.

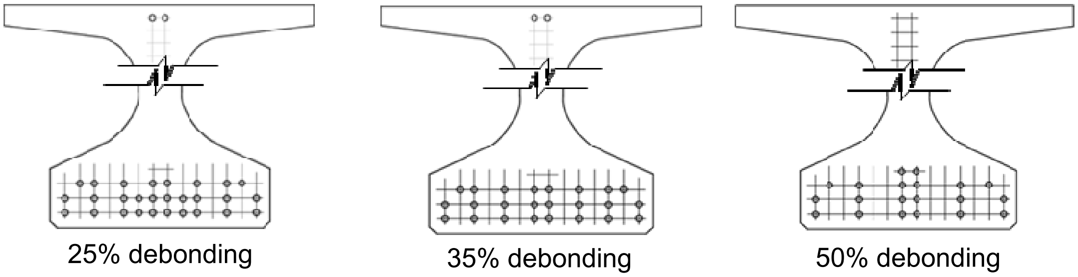
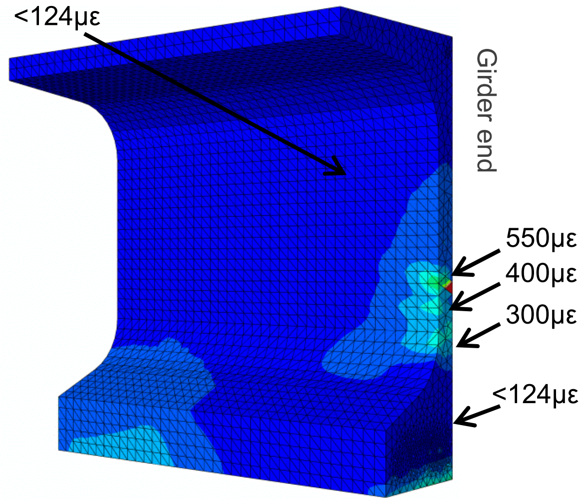
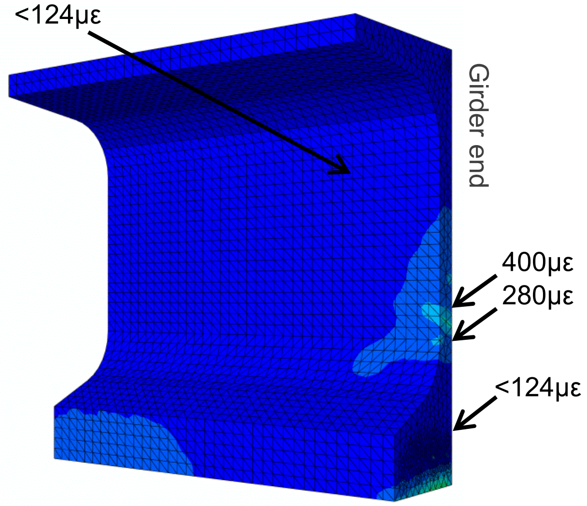

25% debonding 35% debonding 50% debonding

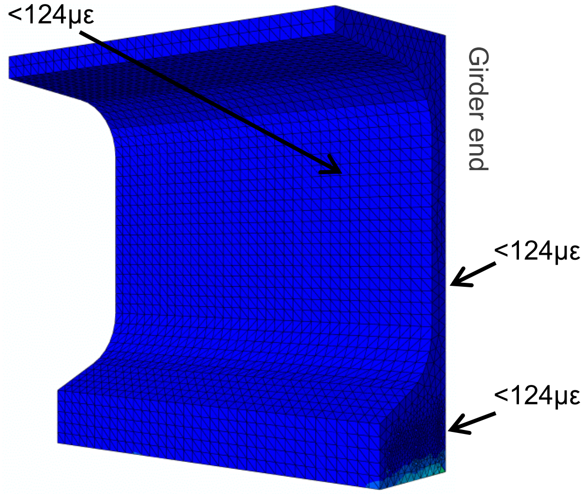
Figure 10 - The pattern of strands bonded at the girder end.



25% debonding



35% debonding



50% debonding

Figure 11 - Principal tensile strains with various levels of debonding.

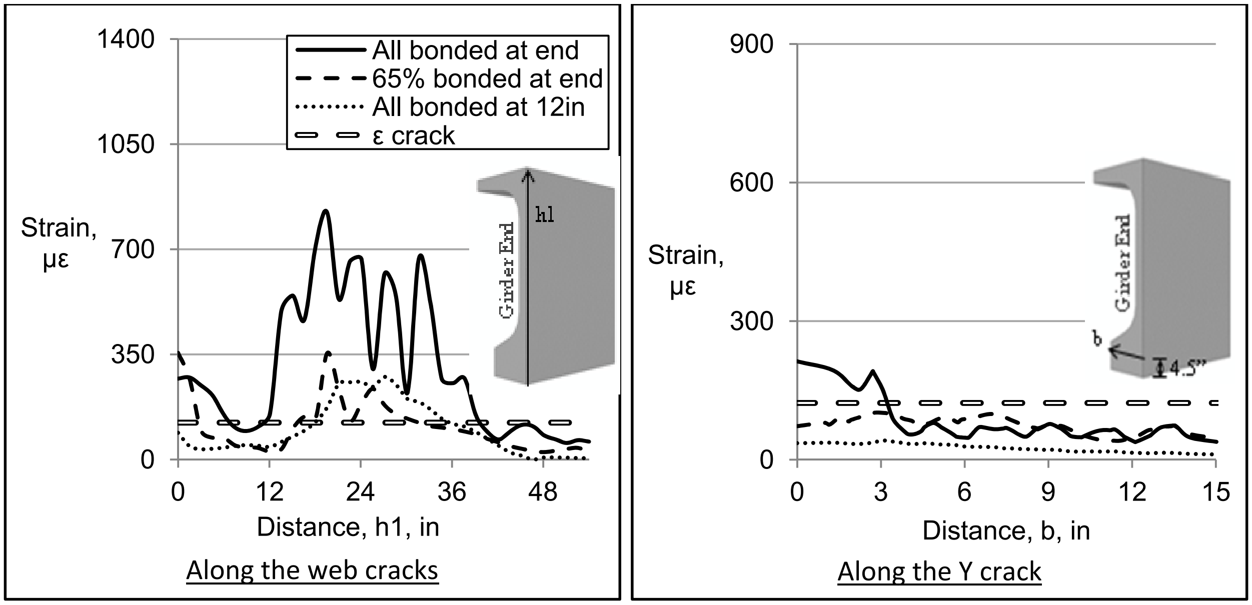


Figure 12 – Principal tensile strains along the girder depth with debonding.

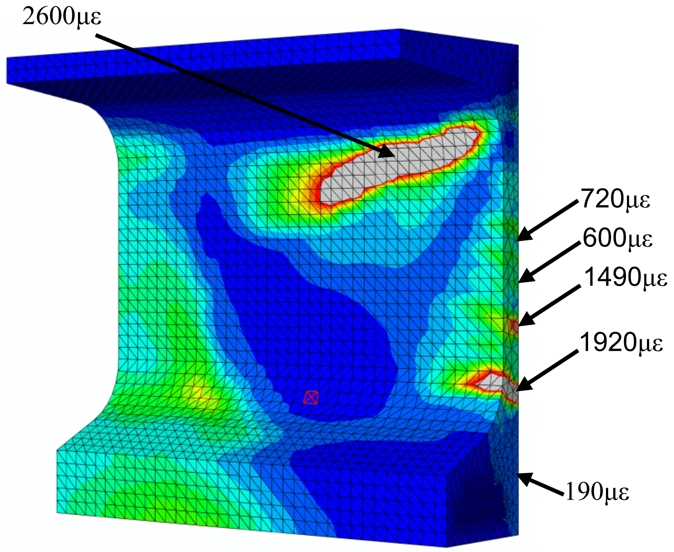
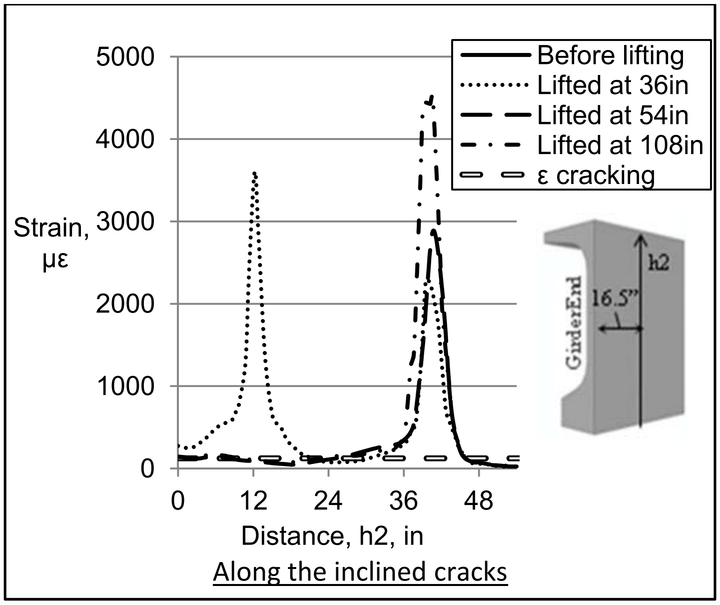


Figure 13 – Principal tensile strains after the girder is lifted at 54in from the end.



Along the inclined cracks

Figure 14 - Amplification of principal tensile strains with varying lifting locations.