STRESS ANALYSES OF THE ANCHORAGE ZONES IN PRE-TENSIONED CONCRETE BRIDGE GIRDERS CONTAINING PARTIALLY DEBONDED STRANDS

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ABSTRACT

Debonded strands are effective in reducing tensile stresses in the end regions of pre-tensioned concrete members. However, cracking in the anchorage zone of beams with unbonded strands has been observed during production. Shear reinforcement, skew angle, debonding material, strand spacing, etc., can all contribute to beam-end cracking. Unfortunately, design recommendations for debonded strands do not take into account such parameters and mainly address the issue of reduced shear strength. The effect of debonded strands on beam end damage during release was studied through nonlinear finite element simulations of two case studies. The cases deal with skew bridge beams with U- and box-type cross sections that experienced damage during production. The effect of flexible tight-fitting and oversized debonding material, strand debonding pattern and beam skew were evaluated. The models were developed with parameters from experimentally calibrated models of small-scale beams. Results show that the dilation of debonded strands with tight soft sheathing is a source of damage in the beam-end region and that this effect can be reduced by using oversized sheathing. The pattern of debonded strands can also have a noticeable effect and could be a source of beam-end shear cracking. Beam skew can add to the noted dilation effects and cause further damage. Thus, the use of rigid sheathing and a staggered pattern for debonded strands were identified as effective mechanisms to reduce beam-end damage.

Keywords: Debonded, Finite Element, End-cracking, Prestressed, Strand, Beam

INTRODUCTION

The release of prestressing strand in concrete beams leads to a high stress state in the anchorage zone that can result in concrete cracking. Such initial cracking can increase transfer and development lengths, minimize expected capacities and accelerate deterioration. There are many factors that can contribute to beam-end cracking, such as concrete strength, release procedures, restraint from unreleased strand, shear reinforcement, strand spacing, beam skew, etc. The use of debonded strands to reduce tensile stresses in beam end regions has become an effective way to minimize beam end cracking. However, perhaps as a consequence of the increased girder sizes or increased levels of prestressing, cracking in the anchorage zone of beams with unbonded strands during production (see Fig. 1) has recently risen as a major concern[1,2,3]. Unfortunately, guidelines on the limits and effects of strand debonding in codes such as the AASHTO Specifications[4] do not take into account the noted parameters and mainly address the issue of reduced shear strength and only minimally address issues that may be a source of damage during production.

a) Skew Box-beam[1] b) Skew U-beam[2]

Fig. 1 Damage at beam ends of prestressed bridge girders during production

Strand debonding is normally achieved by placing plastic sheathing around the strand. Two options are commonly used: flexible split-sheathing with a tight fit around the strand, or a more rigid preformed plastic tube with an inside diameter greater than the strand. These options are intuitively thought to have different efficiency. Specifically, the flexible (softer) tight-fitting debonding material is thought to have lower debonding efficiency as mechanical interlock shear resistance may develop and bond may not be completely eliminated. On the contrary, stress transfer will not occur within the debonded region if an oversized preformed tube is used since the strand is physically separated from the concrete.

There have not been many studies conducted regarding the sources of end cracking in prestressed concrete girders during production. One of the challenges is the multiple possible parameters of influence and that the damage is limited to the girder end, making large-scale experimental approaches cost prohibitive. Numerical approaches validated with small-scale experiments or a limited set of large-scale experiments have thus been favored. One of the most recognized works is the one conducted by Mirza and Tawfik[5], who developed a one-dimensional numerical model to study the vertical cracks that appeared in the end regions of pre-tensioned members during strand release. They found that such problem can be reduced if longer strand free length is provided. Kannel et al.[6] used three-dimensional (3D) linear-elastic finite element (FE) simulations to evaluate the effect of strand release sequence on prestressed concrete beam end cracking and recommended approaches to reduce such damage. Both of these studies assumed perfect bond between the strand and concrete, and the models by Kannel et al. used one dimensional (truss) elements to simulate the strands. Thus, the lateral behavior of strand during release, which is a potential source of damage, was not considered. It follows that even less is known about the performance of debonded, or shielded strand. A recent work by Sun[7] has shown that the lateral behavior of the strand and the bond friction phenomena between strand and concrete can considerably increase tensile stresses in the concrete and can thus be a major source of damage in beam ends. As a result, it is of importance and necessity to evaluate the bond simulation with 3D strand models.

This paper reports on experimentally calibrated nonlinear 3D FE models developed using the program Abaqus[8] to investigate the effects of sheathed strand on beam-end cracking within the context of two case studies: a 48”x39” (1220 mm x 990 mm) box beam[7] and a 56”x80” (1422 mm x 2032 mm) U-beam[9], for which evidence of beam-end cracking exists (Fig. 1).

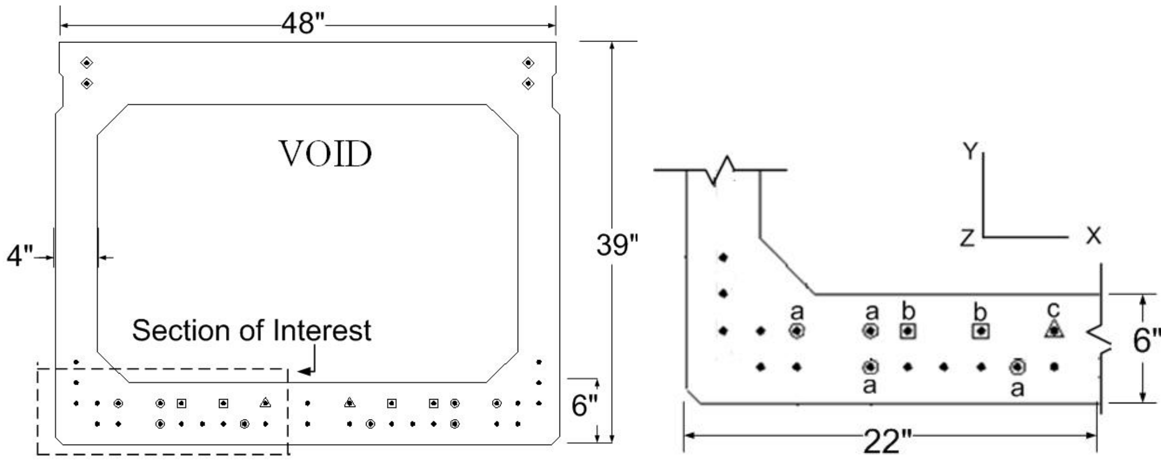
PROBLEM BACKGROUND FOR CASE STUDIES

BOX-BEAM CASE STUDY

This study was conducted based on the end cracking problem faced by the Michigan Department of Transportation (MDOT) during production[1] of an AASHTO prestressed concrete box-type bridge girder (see Fig. 1(a)) with outside cross-section dimensions of 48”x39” (1220 mm x 990 mm), see Fig. 2(a). The total girder length was 117 ft (35.7 m) and the skew angle at both ends was 40^{o}. The girder used 0.6-in. (15.2 mm) diameter Grade 270 (1860 MPa) strands and debonding was accomplished using flexible (tight fitting) sheathing. 14 of 36 strands in the bottom flange were unbonded. Thus, the total number of unbonded strands was 38%. The percentage of debonded strand per row was: 24% in row 1 and 67% in row 2. Such design exceeded limits in AASHTO LRFD specifications for debonded strand (less than 40% per row and less than 25% total). The unbonded lengths are given in Table 1 with reference to Fig. 2(b). The concrete compressive strength at release was 4600 psi (31.7 MPa), and the initial strand prestressing level was 0.75 f_{pu}, or 202.5 ksi (1396.2 MPa).

U-BEAM CASE STUDY

This study was conducted based on the end cracking problem faced by the Indiana Department of Transportation (INDOT) during production[2,3] of a prestressed concrete U-type bridge girder (see Fig. 1(b)). The dimensions of the U-beam are: 56 in. (1420 mm) wide on the bottom flange, 99.5 in. (2525 mm) wide at the top, 61.5 in. (1560 mm) wide void in the upper part, and a depth of 54 in. (1370). The total girder length was 116’-5” (35.5 m) and the skew angle at both ends was 18°. The cross section of the U-beam is shown in Fig. 3(a). The girder used 0.6-in. (15.2 mm) diameter Grade 270 (1860 MPa) strands and debonding was accomplished using flexible (tight fitting) sheathing. 21 of 57 strands in the bottom flange were unbonded. Thus, the total number of unbonded strands was 37%. The percentage of debonded strand per row was: 20% in row 1, 43% in row 2 and 43% in row 3. Such design exceeded limits in AASHTO LRFD specifications for debonded strand. The unbonded lengths are given in Table 1 with reference to Fig. 3(b). The concrete compressive strength at release was 8,000 psi (55.2 MPa), and the initial strand prestressing level was 0.75 f_{pu}.



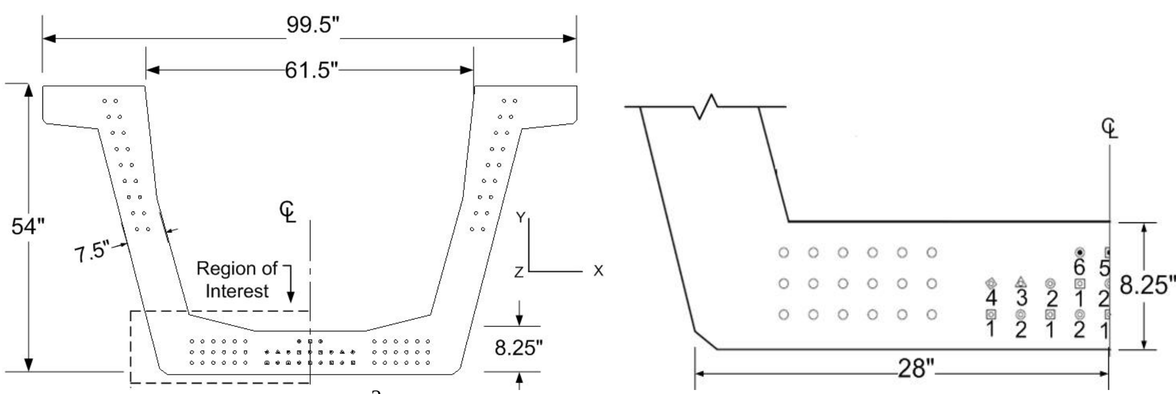
a) Cross section b) Region of interest

Fig. 2 Box-beam: Cross section and region of interest for FE model [7]

Table 1 Debonded strand length in Box- and U-beam units

Box Beam		U Girder			
ID	Length (ft)	ID	Length (ft)	ID	Length (ft)
a	15.5	1	9.0	4	18.0
b	25.0	2	12.0	5	21.0
c	31.0	3	15.0	6	24.0

Note: 1 ft = 0.3049 m



a) Cross section[2] b) Region of interest

Fig. 3 U-beam: Cross section and region of interest for FE model[9]

NUMERICAL MODELS

GENERALITIES

Numerical models were established using the general purpose FE program Abaqus[8]. Three-dimensional continuum elements were used to model both concrete and strand within the region of interest (see Fig. 2(b) and Fig. 3(b)). Continuum 3D eight-node linear brick reduced integration (C3D8R) elements were used. The strand was modeled as a cylindrical rod with an equivalent cross-sectional area equal to the actual strand. The prestress in the strand was introduced in the model by defining an initial stress condition so that the strand was stressed at the beginning of the analysis. The equivalent diameter of the rod was 0.5245 in. (13.32 mm) after considering the initial stress due to pre-tensioning. The bond between the strand and concrete along fully bonded regions was simulated with a surface-based contact definition such that the strand and the surrounding concrete surfaces could not penetrate each other in the normal direction. A non-linear friction model, which was controlled by the contact pressure and a friction coefficient, was defined between the two surfaces in the tangential direction. After release, the strand dilates due to its Poisson's ratio and pressure is generated between the strand surface and the surrounding concrete. This pressure was used as the normal pressure needed for the friction model. Friction coefficient values were determined by calibrating the model with experimental data, namely the longitudinal concrete strain profile after transfer. The transfer of the pre-applied stress in the strand to the concrete after release was the only load in the numerical model.

Strand-concrete bond in the debonded region when the strand was to be simulated was debonded with soft (flexible) material was similar to that of the fully bonded condition with one key difference. The difference was that a zero friction coefficient was defined to simulate the eliminated bond strength. However, the prestressing strand and concrete had a tight fit, thus a normal pressure was still generated after release. This approach was used to represent the easily-deformable characteristic of the soft sheathing material. On the other hand, oversized holes (0.6 in. [15.2 mm]) were defined around strand parts that were to be simulated as shielded with an oversized rigid debonding material. Thus the bond mechanism was completely eliminated and there was no interaction between the strand and the concrete even after release.

BOX-BEAM CASE STUDIES

Three Box-beam models were created: 1) As-built model simulation with all features of the real box beam featuring soft (tight fitting) sheathing; 2) Straight beam model (no skew) with all other features as in the as-built model; and 3) As-built model simulating strand debonding with rigid sheathing by providing oversize holes along the strand debonded length.

A view of the typical box-beam FE model is shown in Fig. 4. Half the beam was modeled in the longitudinal direction due to symmetry. The region of high interest (see Fig. 4), which is a rectangle at the corner of the cross-section with dimensions of 22 in. (560 mm) by 8.25 in. (210 mm) as shown in Fig. 2(b), was modeled with solid elements as described in the

Generalities section. The length of the solid-concrete part was 35'-10" (10.92 m), and this length covered the longest debonded strand length (see Table 1). The strands outside and beyond the region of interest were simulated with truss elements. The remaining concrete part was modeled using shell elements with a thickness of 4 in. (100 mm) and 6 in. (150 mm) for the vertical and horizontal sides of the box-beam (see Fig. 4), respectively. Passive reinforcement was modeled with embedded truss elements in the solid element region and with a smeared reinforcement layer for the shell element regions. End-blocks and intermediate diaphragms were not considered to significantly affect prestress transfer in the beam-end region and were thus not included in the model. Reinforcement for composite action was not considered.

The diameter for 3D strands (cylindrical rods) used in the models was 0.5245 in. (13.32 mm), which corresponds to the stressed state of the strand. As previously noted, for partially debonded strands, the coefficient of friction between the strand and concrete surfaces along the unbonded length was zero and for the fully bonded length was 0.38. This value was obtained from calibrated numerical models using experimental data[7].

It is of interest to simulate the potential damage to the box beam, thus the definition of realistic material behavior in the models is very important. Unfortunately, the large number of elements along the strand to concrete interacting surfaces led to excessive computational demand and convergence problems that hampered successful implementation of a nonlinear concrete model definition. As a result, the concrete material was defined with elastic properties. The viability of identifying induced cracking even when using linear-elastic material properties were verified through additional numerical analyses[7]. The prestressing and passive steel reinforcement were also modeled with linear elastic properties since their behavior is within the proportionality limit. The elastic modulus and Poisson's ratio values used in the models were: 3,866 ksi (27 GPa) and 0.2 for concrete, and 29,000 ksi (200 GPa) and 0.3 for steel.

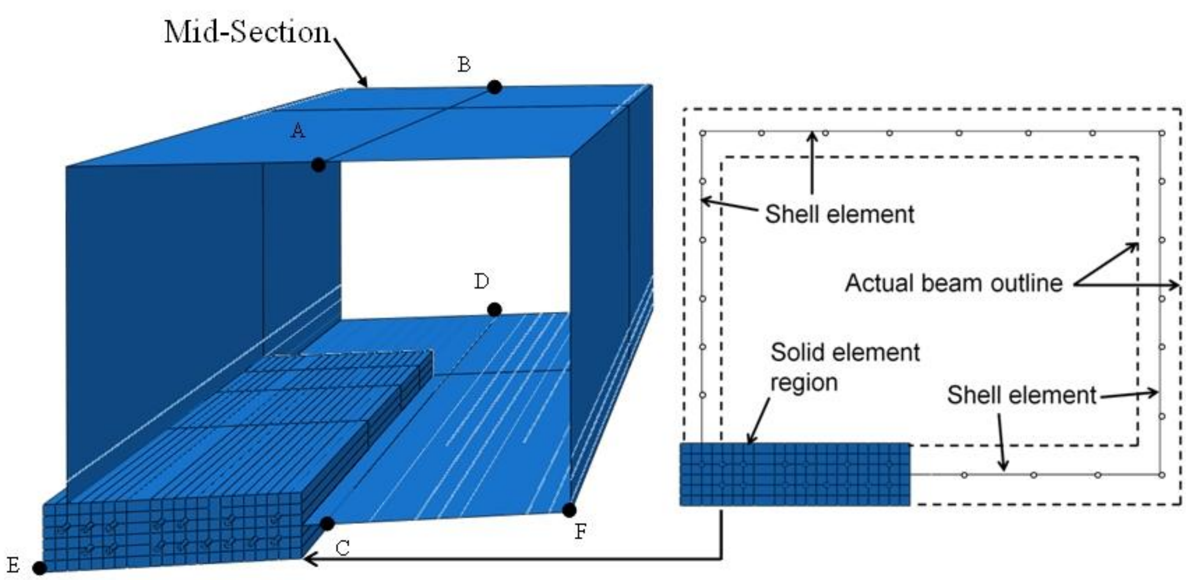


Fig. 4 View of Box-beam FE model and region of high interest

The shell and continuum elements were connected using a shell-to-solid coupling constraint. Symmetry in the longitudinal direction was defined. The beam was restrained from lateral movement at location C (see Fig.4), and the vertical movement was restrained along the front-bottom edge of the beam of the solid elements and along the front edge of the shell elements (from C to F [see Fig.4.]).

U-BEAM CASE STUDIES

Four U-beam models were created: 1) As-built model simulation with all features of the real box beam featuring soft (tight fitting) sheathing (UCS); 2) As-built model simulating strand debonding with rigid sheathing by providing oversize holes along the strand debonded length (UCR); 3) Model with a staggered arrangement pattern for the deboned strands with flexible (tight fitting) sheathing (USS); and, 4) Model with a staggered arrangement pattern for the debonded strands with rigid (oversize holes) debonding (USR).

A view of the typical U-beam FE model is shown in from Fig. 5. The concrete part was entirely modeled using 3D continuum solid elements. A quarter of the beam was modeled due to symmetry considerations in the longitudinal direction and in the transverse direction (upon neglecting the effect of the small skew angle.) The region of interest (see Fig. 5), which is a rectangle at the corner of the cross section with dimensions of 28 in. (710 mm) by 8.25 in. (210 mm) as shown in Fig. 3(b), was modeled with a considerably smaller mesh than the rest of the concrete part.

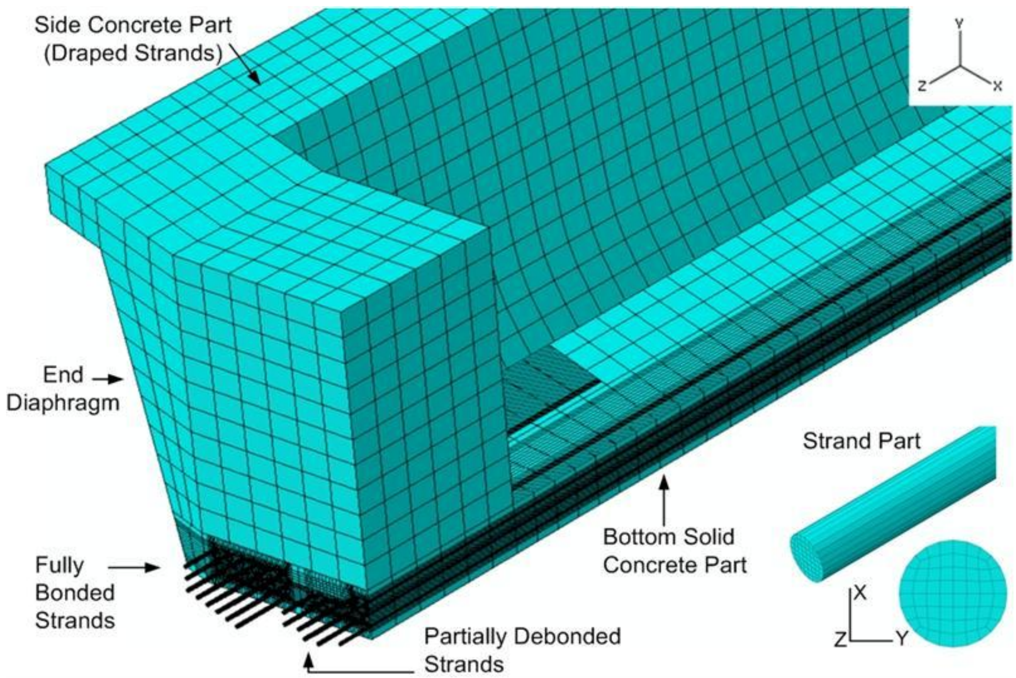


Fig. 5 View of as-built U-beam FE model

The fully bonded strands located in the bottom flange (see Fig. 3-b) were modeled using 3-D solid elements up to 4 ft (1220 mm) from the beam end. The strand unbonded lengths for the as-built U-beam models are shown in Table 1. The debonded lengths for the USS and USR model were one-quarter of the original L_u (Table 1) to reduce the size of the model and thus computational demand. The partially debonded strands were modeled with 3D solid elements (and contact interaction definitions) for the first 360 in. (9145 mm) from the beam-end since this length covered the longest debonded length (24 ft [7.32 m]) and the estimated transfer length. The strand beyond the noted distances defining the regions of high interest were modeled as discrete truss elements embedded in the concrete region using constraints that connected the linear elements to the 3D strand part. The draped strands at beam side (see Fig. 5) were modeled as truss elements embedded in the concrete region as well, and the hold down point was located at about 47'-3.5" (14.4 m) from the releasing end. The end block diaphragm was included in the model (see Fig. 5) and its length was 24 in. (610 mm).

The diameter for 3D strands (cylindrical rods) was of 0.5268 in. (13.4 mm). The coefficient of friction between the strand and concrete surfaces along the unbonded length was zero and for the fully bonded length was 0.59. This value was obtained from experimentally calibrated numerical models. Details of this process are to be presented in future communication. The oversize hole to simulate rigid debonding material was 0.6-in (15.2 mm) in diameter.

The strand was modeled using linear elastic material properties as defined for the Box-beam models. The concrete part was assigned a nonlinear concrete model, namely, the concrete damaged plasticity (CDP) model available in Abaqus[8]. Successful implementation of the CDP model was possible based on the lessons learned on the box-beam studies, which led to reducing model size in the contact interaction region by modeling the strands outside of the region of interest with truss elements. This reduced the number of elements used for the nonlinear friction-contact interaction formulation.

SIMULATION RESULTS

BOX-BEAM CASE STUDIES

The possible cracking region in box-beam models was investigated by defining an upper limit in the contour plots of maximum principal stresses. The upper limit of concrete tensile strength was estimated to be 508 psi (3.5 MPa). Contours plots of the maximum principal stresses in the solid concrete regions of the models with flexible sheathing (tight fitting) and with rigid sheathing are compared to the observed damage in Fig. 6. The grey regions in the contour plots in Fig. 6 represent values above the concrete's tensile strength.

The simulation results shown in Fig. 6 reveal close resemblance with the observed damage. The predicted damage region in the as-built model with debonded strand using soft tight-fitting sheathing is larger than the case when oversized rigid debonding is simulated. The high stresses observed in the contour plot follow from boundary effects that result from the twisting of the skew girder upon release and the fact that the diaphragm was not included.

Results for the third model (straight), not provided here for brevity, supported that damage was the result of a combination of the stress states induced by the dilation from debonded strands with flexible sheathing and the from beam twisting due to the large beam skew.

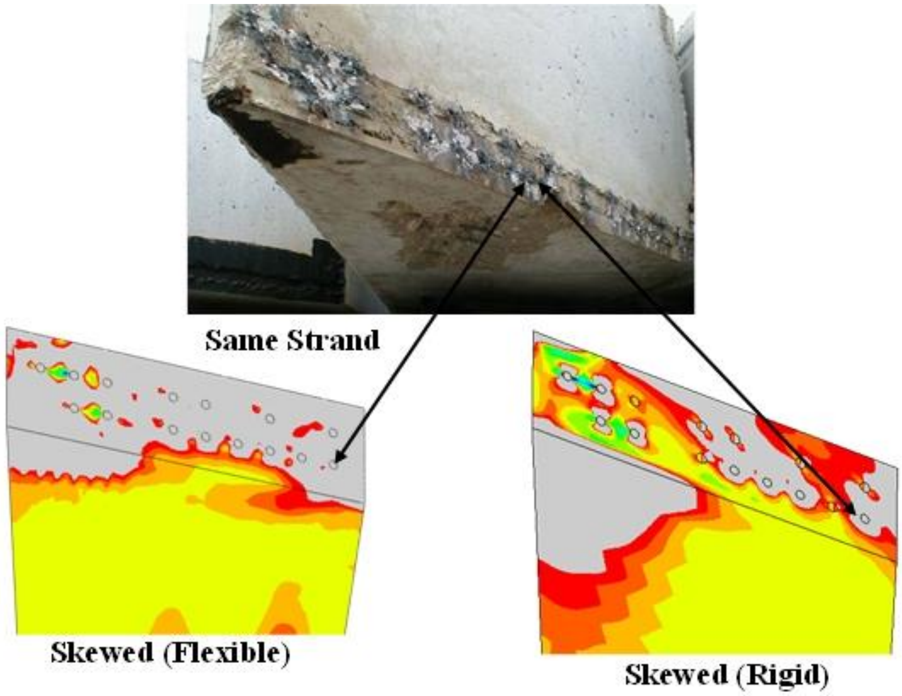


Fig. 6 Observed and predicted damage for the Box-beam case studies

U-BEAM CASE STUDIES

The possible cracking region in U-beam models, which utilized a nonlinear concrete model, was assessed by comparing the observed damage to the maximum principal plastic strains. This comparison is shown in Fig. 7. The upper limit of concrete tensile strength was estimated to be 670 psi (4.62 MPa). It can be seen that the high plastic strains in the simulation results closely relate to the observed damage at the end of the U-beam.

Results for the four U-beam models are compared in Fig. 8, which shows that the damage predicted in the as-built model (UCS) can be minimized by using oversize rigid debonding (UCR). Staggered distribution of the prestressing strands (even if debonded with flexible sheathing) can also help, as shown in the results for the USS model. Damage seems to be minimized the most if the strands are debonded with a rigid oversize sheathing and placed in a staggered pattern along the flange (USR model). The models do show high strains in the corner along the transverse symmetry line, which indicates that the skew effect is significant. It was observed that this boundary effects decay rapidly into the beam. However, the negative effects from the dilation of strands debonded with a flexible sheathing continue for the entire debonded length region, which clearly further increases the propensity for damage.

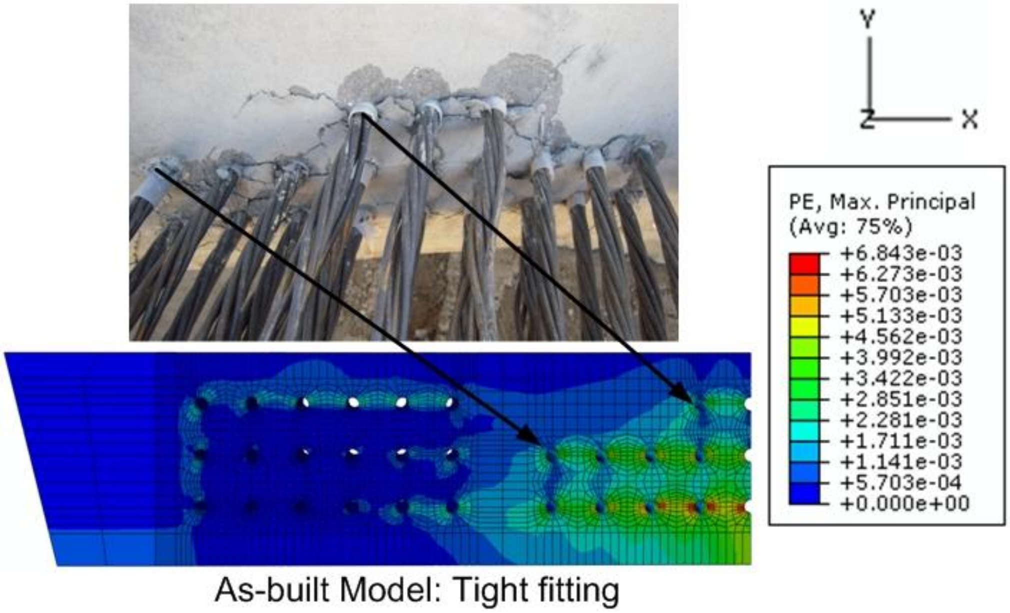


Fig. 7 Observed damage and maximum principal plastic strains for as-built U-beam model

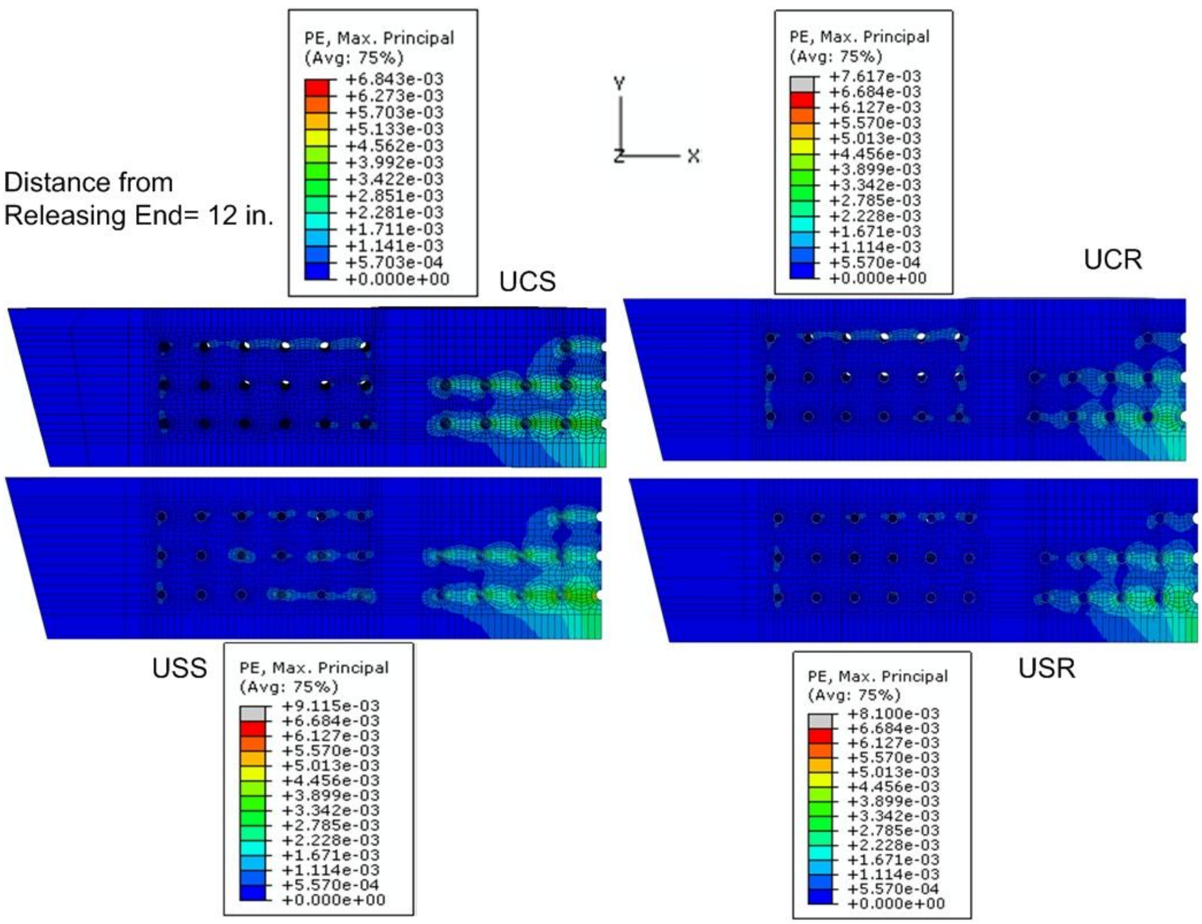


Fig. 8 Maximum principal plastic strains for U-beam models 12 in. (305 mm) from beam end

CONCLUSIONS

Experimentally calibrated nonlinear finite element models were developed to investigate the effects of sheathed strand on beam-end cracking within the context of two case studies for which evidence of damage exist. The effects of debonding material, debonded strand placement and skew angle were considered. Numerical simulations on the as-built conditions of a skew a 48”x39” (1220 mm x 990 mm) box beam and a skew 56”x80” (1422 mm x 2032 mm) U-beam were able to closely replicate the observed damage in the bridge girders.

Results from the Box-beam simulation models showed that the dilation of the partially debonded strands using soft sheathing in combination with a large skew angle was the source of damage in the beam-end region. The damage from strand dilation, which is maximized due to the lack of bond, was also shown to be the source of damage for the U-beam case, in this case prompted by the close proximity of the debonded strands within a region. Simulation of strand debonding with an oversized rigid material showed that this option can significantly decrease the tensile stresses at the beam end. The U-girder simulations provided a better understanding of the influence of strand location in beams containing partially debonded strands. Simulations with a staggered arrangement for the debonded strands revealed a significant decrease of tensile stresses in the anchorage region. The staggering approach was even more effective when a rigid oversized debonding material was simulated.

The presented studies indicate that, while effective in many cases, strand debonding with soft tight-fitting sheathing can induce significant damage in the anchorage zones of prestressed concrete girders; particularly when the girders feature large skews or the debonded strands are closely grouped together. The use of rigid oversized debonding, while more cumbersome in its installation, should be strongly considered when the design has the above noted features. In addition, staggering of the debonded strands within the beams flange was found to be beneficial in reducing anchorage zone stresses and it is thus recommended.

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