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Seismic behavior of precast concrete pier cap-beam-to-column joints with horizontal and vertical prestressing

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ABSTRACT

This paper presents numerical investigations of the behavior of beam-column joints for bridge substructures subjected to cyclic loading. The objective of this research is to assess the performance of a precast substructure system for moderate seismic regions wherein both the columns and the pier cap may be prestressed. A state-of-the-art finite element package for structural concrete was first used to simulate recent experiments investigating the behavior of monolithic and precast bridge cap-beam-to-column connections with varying degrees of horizontal prestress in the cap beam. To assess the ability of numerical models to represent and predict seismic behavior, various numerical modeling techniques have been explored. The behavior of different material models for cracking and compression softening of concrete as well as bondslip has also been studied. Further investigations into the modeling and design issues of precast substructure connections with vertical and horizontal prestressing are then presented. Key parameters include confinement provisions, the use of partially bonded and unbonded reinforcement, and the level of effective prestress.

INTRODUCTION

Precasting bridge substructure offers many practical advantages such as construction efficiency and durability. A number of different systems have been developed in recent years primarily for non-seismic regions (Billington et al. 1999, LoBuono et al. 1996). Despite the emphasis on *monolithic* behavior in current seismic design practice, the potential of precast systems (which are inherently not monolithic) should be considered. The efficiency of precast construction could greatly speed up the replacement of collapsed or heavily damaged bridges after earthquakes. In addition, the controlled environment of precast plants enable precast systems to take full advantage of the rapid development of high performance construction materials which exhibit qualities desirable to seismic resistance such as increased toughness and ductility.

The *post-tensioning* joining the precast segments may also improve the seismic behavior of the system in several ways. Prestressing increases the shear capacity of the connection regions, which may enable a substantial decrease in the amount of shear reinforcement required in the often-congested connection regions. The improvement in the joint performance through post-tensioning has been demonstrated in recent experiments conducted at University of California at San Diego (UCSD) (Sritharan et al. 1997). The use of *unbonded* post-tensioning tendons has the additional benefit of greatly reducing residual displacements. As an unbonded tendon generally stays elastic before the ultimate capacity of the system is reached, after an earthquake the structure should return to its original position and have its initial stiffness restored. Granted the advantages of this system, many issues associated with its use need to be addressed, such as the low energy dissipation capacity and the determination of optimal prestress levels.

The research presented herein is conducted for the potential implementation of a substructure system of both precast columns and precast pier caps for moderate seismic regions. This system may have but does not require prestressing both horizontally in the pier cap and vertically in the columns. The combination of high performance/high strength concrete with varying levels of prestress has the potential for good seismic behavior. Promising seismic performance of vertically post-tensioned bridge piers has been demonstrated in recent test programs conducted in Japan (Ikeda 1998, Ito et al. 1997). Using state-of-the-art nonlinear finite element analyses as the major tool, the current research builds on past experimental studies and expands their scope to examine the many issues involved with the new system of interest.

In order to assess the available numerical models in representing the behavior of structural concrete under cyclic loading, finite element analyses were performed using the package DIANA to model a set of experiments on cap-beam-to-column bridge connections carried out at UCSD (Sritharan et al. 1997). Results of the simulation of these experiments and sensitivity studies of the various material parameters used in the analyses are shown. Preliminary investigations in the modeling and design issues of a precast, post-tensioned bridge substructure system are presented and discussed.

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SIMULATION OF EXPERIMENTS OF CAP-BEAM-TO-COLUMN BRIDGE CONNECTIONS

Background on the experiments

The first phase of this study involves the simulation of experiments conducted at UCSD by Sritharan et al. on cap-beam-to-column bridge connections subjected to cyclic loading in the transverse direction (Sritharan et al. 1997). The specimens were redesigns of a typical cap-beam-to-column joint in the Santa Monica Viaduct in Los Angeles, California. Three redesigns detailed to have about the same capacity were made: the first with only ordinary reinforcement, the second with partial prestressing across the cap beam, and the third with full prestressing connecting precast cap beam segments to the cast-in-place column. Figure 1 shows the redesign with full prestressing across the cap-beam.

The three redesigns all exhibited good performance and high ductility under cyclic loading. As they differed only in the design of the *cap beam* but not the column, the load-deflection curves of the specimens were very similar. The use of prestressing along the cap beam not only resulted in great savings in joint shear reinforcement, but also significantly reduced the damage in the connection region (Sritharan et al. 1997).

Finite element model

The finite element model used for the simulation of the experiments is shown in Figure 2. The 2-dimensional mesh employs quadrilateral 8-noded isoparametric plane stress elements. All the longitudinal and shear reinforcements were included in the model as embedded bar elements. As in the experiment, an axial load of 400 kN was applied to the top of the column to represent the dead load of the superstructure, and cyclic loading was applied to the top of the column using the displacement-control method.

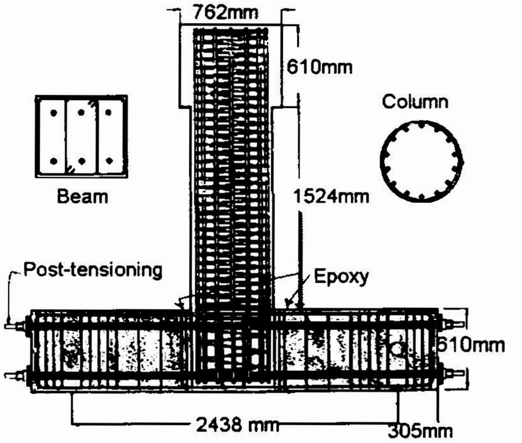

Figure 1. Specimen with horizontal prestress across the cap beam. (adapted from Sritharan et al. 1997)

Two types of material models for concrete were adopted in the analyses. The first is based on an *incremental formulation*, where the constitutive relations are expressed in terms of the elastic and the inelastic components of the total strain obtained from strain decomposition (TNO 1998); the second is based on a *total-strain formulation*, where the constitutive relations are formulated in terms of the total strain (Feenstra 1997). Both formulations employ a smeared crack model for tension. For compression, the incremental formulation uses a plasticity-based approach, whereas the total-strain formulation is based on the modified compression field theory (Vecchio and Collins 1993). The behavior of the reinforcements is represented by a plasticity model incorporating the effect of strain hardening. Interface elements were used to model the epoxy between the precast segments in the fully prestressed specimen. The effect of bondslip was explored in a model where the reinforcements were represented by discrete truss elements, and the bond between the concrete and steel was modeled as interface elements with a specified shear stress-slip relation.

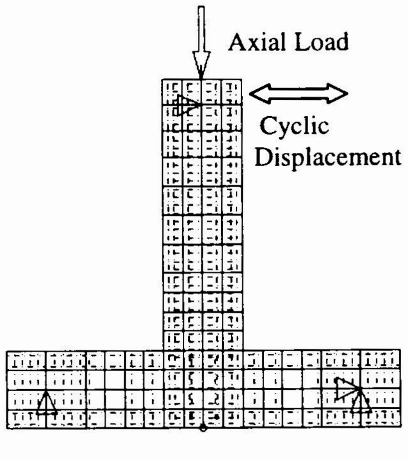

Figure 2. Finite element model. (solid line: mesh; dashed line: reinforcement)

Results

Results from the finite element models are generally in satisfactory agreement with results from the experiment. Figure 3 shows a comparison of the experimental and numerical response for the ordinarily reinforced specimen using respectively the incremental formulation and the total-strain formulation for the concrete material model. The use of the two different concrete models caused a significant difference in the overall hysteretic behavior, which arose from the different unloading behavior of the two formulations. Elastic unloading is implemented in the incremental formulation, whereas secant unloading is implemented in the total-strain formulation (TNO 1998). The actual unloading behavior of concrete lies between the extremes of elastic and secant unloading. The overall response of the model shows preliminarily that the adoption of elastic unloading results in an unloading response that is too stiff and leads to extraneous energy dissipation. On the other hand, the use of secant unloading can capture the stiffness degradation of the concrete in unloading, leading to an overall response more closely related to the experimental findings. The initial stiffness from the finite element analyses was comparable to that observed in the experiment, but the strength was higher since the concrete material models did not account for the effect of compression softening.

Figure 4 shows the effect of compression softening using the total-strain based concrete model. Incorporation of the compression softening effect caused a decrease in the ultimate strength and a reduction in the unloading stiffness, which resulted in a better correspondence between the response from the experiment and the finite element model. Bondslip and the Bauschinger effect of steel were not represented. The total-strain model was found to be more robust than the incremental model, which had convergence problems when the effect of concrete softening was included.

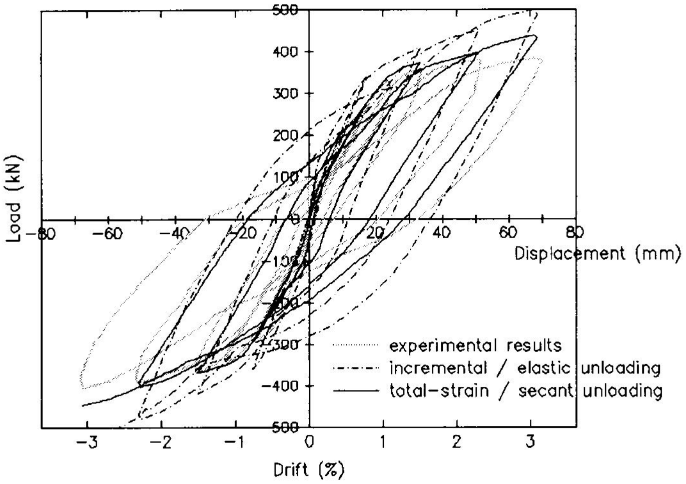

Figure 3. Comparison of load-deflection curves from experiment and finite element model with incremental and total-strain formulations for the concrete.

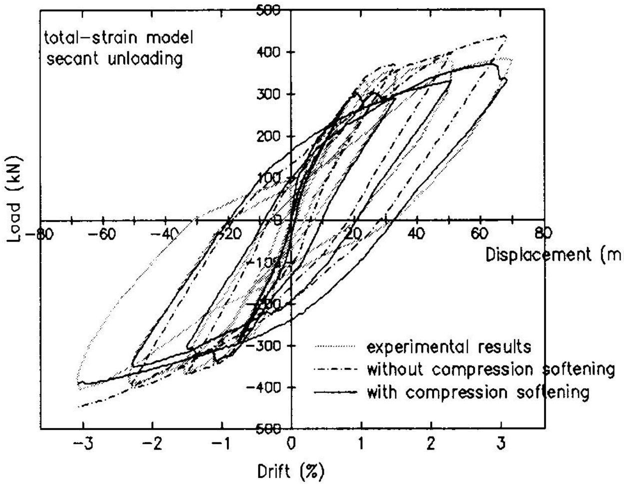

Figure 4. Comparison of load-deflection curves from experiment and finite element model with and without compression softening for the concrete.

Figure 5 shows the load-deflection curves for numerical studies of the three redesigns of the actual bridge connection with different degrees of prestressing across the cap beam. The total-strain concrete model with compression softening was adopted in the analyses. The three redesigns have similar load-deflection behavior, with the fully prestressed unit exhibiting slightly higher energy dissipation than the other two units. This is consistent with the trend observed in the experiment. The crack patterns obtained from the finite element analyses also compare favorably with observations in the experiment, with significantly reduced joint cracking in the units with prestressing across the cap beam. The interface between the precast cap-beam segments and the column in the fully prestressed redesign was found not to be critical in both the numerical and the experimental results, as the epoxy used was stronger than the concrete.

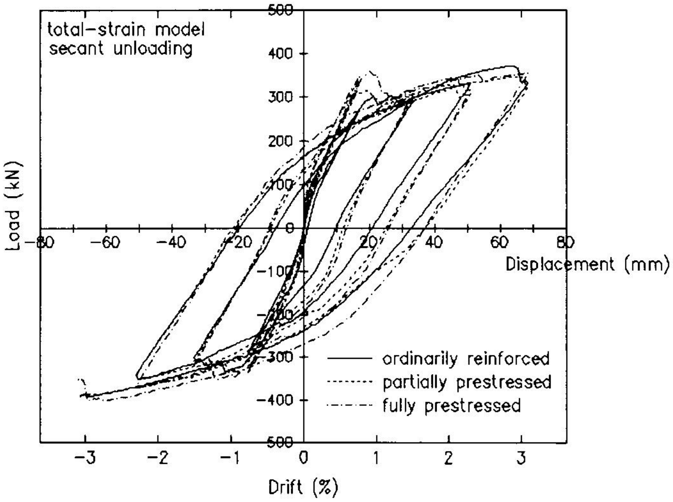

Figure 5. Comparison of load-deflection curves for the three redesigns with different levels of prestressing from finite element analyses.

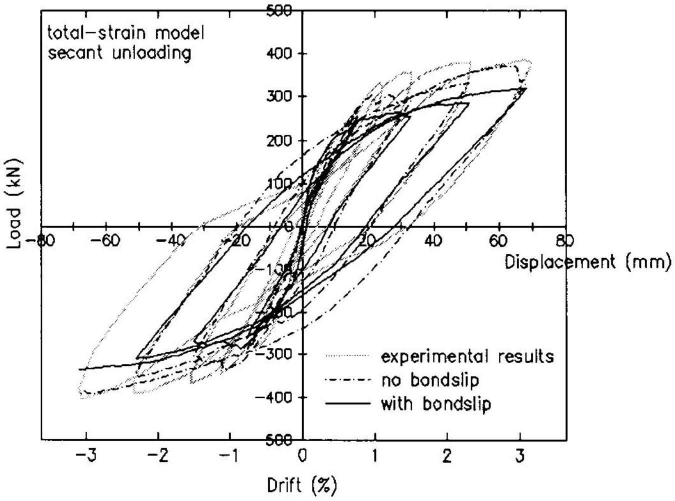

Figure 6. Comparison of load-deflection curves from experiment and finite element model with and without bondslip.

Figure 6 shows the influence of bondslip on the overall response of the model for the ordinarily reinforced redesign. Bondslip is generally regarded as a major factor causing pinching in the hysteretic response. The modeling of bondslip resulted in a reduction in both strength and energy dissipation. Bondslip was recorded in the finite element analyses along the bars, but did not cause major pinching in the load-deflection response. Severe pinching was also not observed in the experimental response as the specimens were adequately designed for shear. Two factors contribute to the extra energy dissipation observed in the finite element model as compared to the experiment: first, the bondslip model did not account for degradation in the shear stress-slip relation; second, the Baschinger effect of the steel was not modeled. The incorporation of these two effects should further improve the performance of the finite element model to capture and predict real behavior.

PRELIMINARY INVESTIGATIONS OF PRECAST, POST-TENSIONED SUBSTRUCTURE SYSTEM

The insights gained in the simulation of the experiments on the cap-beam-to-column bridge connections can directly be applied to the investigation of the precast, post-tensioned bridge substructure system. However, in order to use finite element analyses to address various design issues associated with the potential implementation of the system in seismic regions, some additional modeling issues specific to these systems need to be addressed.

Bonded versus unbonded post-tensioning

There are different advantages and disadvantages associated with the use of bonded versus unbonded vertical post-tensioning for seismic resistance. Apart from the axial force introduced by the prestress, bonded post-tensioning behaves like mild reinforcement, providing reasonably high energy dissipation capacity due to the yielding of the steel (Figure 7). A high energy dissipation capacity introduces a higher effective damping, which would lead to a lower maximum displacement. However, the yielding of the tendons results in the loss of effective prestress, which may be detrimental to structural response.

Unbonded post-tensioning generally does not yield before the ultimate capacity of the system is reached, since strain extension is distributed equally throughout the length of the tendon. The stress in the post-tensioning increases slowly and remains in the elastic range, resulting in a nonlinear elastic load-deflection behavior under cyclic loading (Figure 8). The residual displacement is hence minimal, and the system retains its initial stiffness as it returns to the equilibrium position after an earthquake. The lack of yielding means there is little opportunity for energy dissipation, which results in a reduced effective damping and accordingly increased maximum displacement.

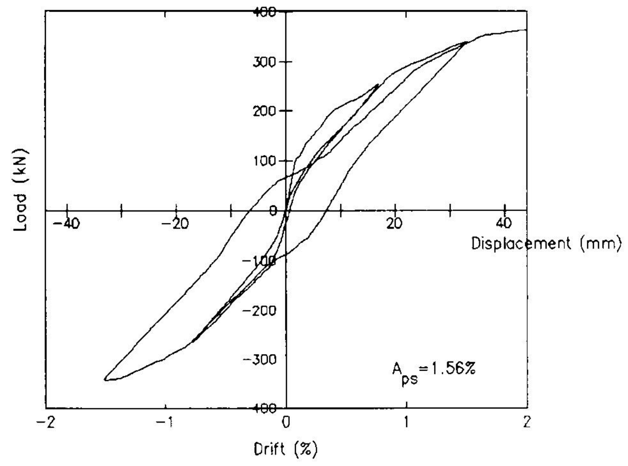

Figure 7. Response of system with bonded vertical post-tensioning from finite element analysis.

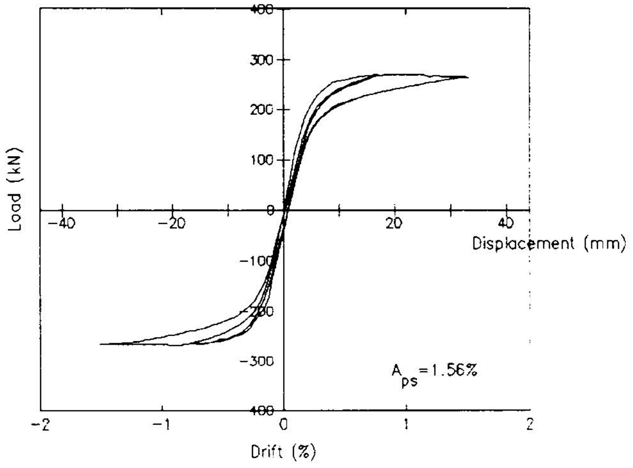

Figure 8. Response for system with unbonded vertical post-tensioning from finite element analysis.

Figure 7 and Figure 8 show the load-deflection behavior of a system with bonded and unbonded vertical post-tensioning. The finite element model shown in Figure 2 was used, with the longitudinal column reinforcement replaced respectively by bonded and unbonded tendons. The same reinforcing ratio and prestressing force were used in each case. The bonded post-tensioning system achieves a higher ultimate moment capacity than the unbonded system, since the stress in the tendons has little increase in the unbonded system and the concrete crushes far before the ultimate strength of the tendon is attained.

A viable option for a precast, post-tensioned substructure system might be a hybrid system taking advantage of both bonded and unbonded reinforcement. Unbonded post-tensioning which gives minimal residual displacement can be used in conjunction with mild reinforcement to ensure adequate energy dissipation. An alternative system might adopt bonded tendons which are debonded close to the connection regions where yielding is expected. Further investigations are required to determine the degree of debonding and the level of initial prestress required to achieve a desired joint performance. Two counteracting factors must be considered in the selection of the initial prestress level for *bonded* post-tensioning. Increasing the level of prestress may reduce joint damage. However, an initial prestress level which is too high may cause early yielding of a bonded tendon, leading to loss of prestress. An optimal level of prestress must be determined to achieve the required capacity without yielding of the prestressing steel.

Joint performance

A main benefit in the adoption of a post-tensioned bridge substructure system is the potential improvement in the performance of the beam-column joint. The introduction of prestress lowers the joint principal tensile stress, which leads to reduced cracking and hence a reduction in joint damage. This effect was demonstrated in the UCSD experiments described earlier (Sritharan et al. 1997). On the other hand, prestressing also causes the increase in the principal compressive stress in the joint, which may lead to brittle failure by the crushing of the joint diagonal strut. This drawback is nevertheless counter-balanced by an additional benefit of the prestressing: prestressing in both the horizontal direction (along the cap beam) and the vertical direction (along the column) creates a biaxial compression stress state in the connection. The active confinement effect introduced by the prestress can improve both the strength and the ductility of the concrete in the connection.

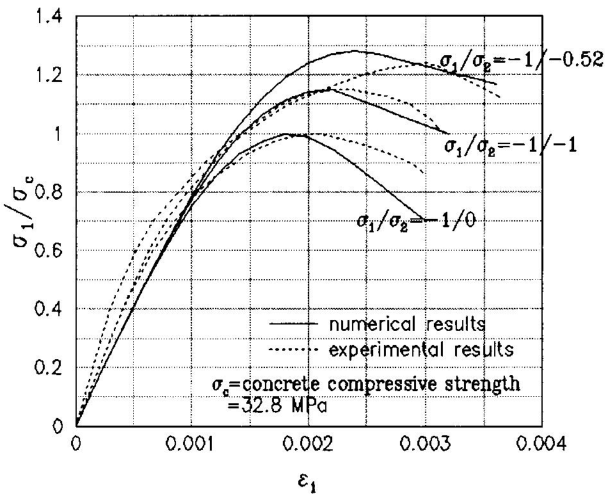

Figure 9. Stress-strain behavior of concrete under biaxial compression.

In order to study the interplay between the various effects of prestressing in the connection region, the adopted material model must be able to reflect the changes in the stress-strain behavior of concrete under biaxial compression. To assess the capabilities of the available material models to capture this effect, single element tests were carried out in which plane stress elements were subjected to a uniform stress state, with loading applied in perpendicular directions according to the following proportions: -1/0 (uniaxial loading), -1/-1 (biaxial loading of equal magnitude), and –1/-0.52 (biaxial loading which causes maximum strength). The properties of the material as well as the proportions of the loading are in accordance with the experiment of Kupfer et al. (1969).

Figure 9 shows the improvement in both strength and ductility under biaxial compression as captured by a concrete model using the total-strain formulation with softening in accordance with Thorenfeldt (1987). The effect of lateral confinement in the total-strain model was accounted for by modifications in the softening curve according to the modified compression field theory (Vecchio and Collins 1993).

Shear transfer between precast segments

A potential failure mode in a precast, post-tensioned substructure system is shear failure at the interface between the precast segments. The precast segments in the substructure system are to be match-cast with multiple shear keys on the surface with epoxy as a jointing material. The compression force introduced by the prestressing through the precast segments provides a large part of the joint shear capacity by shear friction. The prestress level is hence dependent both on the desired overall flexural capacity and the shear capacity between the precast segments. Tests on segmental concrete beams have shown that if only unbonded tendons are used, large cracks may form at the joints due to the lack of stress redistribution. This may lead to shear failure at the interface (Wium and Buyukozturk 1984).

To study the *local* failure modes, the joints between the precast segments can be modeled at a detail level with the actual geometry of the individual keys represented. In such a model, the shear keys are treated as a part of the concrete segments, whereas the epoxy is represented by an interface element embedded with a properly calibrated Coulomb friction model to capture the shear friction effect. Since the response of the entire structure is of interest, a more efficient approach is adopted in the current study where the shear keys *and* the epoxy are combined into an equivalent joint interface element which is embedded with appropriate cyclic shear stress-slip relations. The equivalent interface element can represent the major failure mechanisms of the keyed joints. The deterioration in strength due to the formation of cracks across the keys is accounted for by the deterioration of the shear stress-slip curve. The shear stress-slip relation of the interface is varied according to the degree of confinement, as determined from experiments (Buyukozturk et al. 1990), to represent the increase in the joint shear capacity due to prestressing.

SUMMARY AND CONCLUSIONS

A precast, post-tensioned bridge substructure system is proposed to be a promising system for good seismic performance in moderate seismic regions through the combination of high performance/high strength concrete with varying levels of prestress. The advantages of this system include construction efficiency, reduced reinforcement congestion in the connection, improved joint performance and minimal residual displacements associated with the use of unbonded tendons. Finite element analyses are being adopted to study the various issues including the optimum prestress level, the connection behavior, and the degree of debonding of the tendons.

Through the simulation of experiments of cap-beam-to-column connections subjected to cyclic loading, the capabilities of the available material models were assessed to be generally adequate. The total-strain formulation implemented with secant unloading was found to give a better representation of concrete behavior than the incremental formulation implemented with elastic unloading. Possible improvements to the modeling of structural concrete are being investigated through the inclusion of the degradation in the bondslip relation and the incorporation of the Bauschinger effect for the reinforcing steel. The general load-deflection characteristics of a system with bonded and unbonded tendons can be readily represented by the finite element models. The bonded post-tensioning system exhibits higher energy dissipation and higher residual displacement, and the unbonded post-tensioning system exhibits lower energy dissipation and negligible residual displacement. The increase in strength and ductility of concrete in a biaxial compression state was also shown to be satisfactorily represented, which is crucial in modeling the active confinement introduced by the prestressing in the connection regions. Further studies are underway to gather information for rational designs of this system for a desired joint performance.

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