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Mechanics of the interaction between reinforced concrete beams and rigid stays in span structures of highway overpasses

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Abstract: This article examines the mechanics of interaction between reinforced concrete beams and rigid stays used in span structures of highway overpasses. Theoretical principles of combined work, differential deformation equations, matrix formulation, and numerical simulation are presented. Based on modeling of a three-span system (49.5 + 75.0 + 49.5 m), the effect of stay bending stiffness on the distribution of bending moments and deflections is analyzed. Engineering recommendations are proposed regarding stiffness optimization, anchorage configuration, and joint detailing. The findings contribute to enhancing the reliability and seismic resistance of bridge structures in high-load and earthquake-prone zones.

Keywords: rigid stays, reinforced concrete beams, highway overpass, span structure, bending stiffness, numerical modeling, stress-strain state, MIDAS Civil

1. Introduction

Modern transportation construction imposes ever more stringent requirements on the load-bearing systems of bridges and overpasses, especially under conditions of high traffic density, seismicity, and constrained urban development. One promising direction has been the use of rigid stays within reinforced-concrete span structures, which not only transmit longitudinal forces but also resist bending moments and shear forces, thereby enhancing the spatial stability of the structure. Unlike conventional flexible stays, rigid stays possess inherent structural stiffness and act as struts, carrying not only tensile but also bending loads. This transforms them into full-fledged elements of the stiffness framework, substantially altering the behavior of the span structure. Such a solution is particularly effective for high-speed highway overpasses, where minimizing deflections, redistributing forces, and improving stability are critical [1], [2]. With the advancement of modeling technologies (MIDAS Civil, LIRA-SAPR, SCAD), it has become possible to investigate in detail the mechanics of interaction between reinforced-concrete beams and rigid stays under static and dynamic loading, including seismic effects. Numerical models can identify actual zones of stress concentration, clarify force transfer mechanisms at attachment nodes, and optimize the system configuration [3]–[5]. Research on this topic has broadened in recent years. Zhang Z. et al. [6] and Bahar Esfahani [7] examine the stress-strain behavior of elements in stay-cable bridges with rigid inclusions. Within the CIS, V.G. Petrov [8] and I.A. Semenov [9] were the first to comprehensively consider rigid stays applied to reinforced-concrete beam systems, noting reductions in peak bending moments of 25–30 % compared to traditional beams. These works laid the foundation for a new design approach to composite systems. Beyond their structural and analytical advantages, rigid stays enable a reduction in the mass of the span structure by redistributing loads onto the pylons, improve architectural aesthetics, and decrease pier costs by reducing beam cross-sections [10]. All these factors make them particularly attractive for constructing overpasses in densely populated areas, for rehabilitating aging viaducts, and in seismically active regions. The aim of this paper is to examine the mechanical principles governing the interaction of rigid

stays and reinforced-concrete beams, to formulate a mathematical model of their combined behavior, to analyze the results of numerical simulations, and to provide engineering recommendations for design.

Research objectives:

- To analyze the structural features and connection details;
- To derive the equations describing the joint action of the beam and the stay;
- To perform numerical modeling on the example of a three-span overpass;
- To offer recommendations for the application of rigid stays on high-speed highways.

Thus, this paper is intended to deepen both the theoretical and practical aspects of the mechanics of rigid stays within reinforced-concrete structures, opening new prospects for the optimization of bridge systems.

2. Research methodology

Structural scheme and main elements of the span structure with rigid stays. In modern highway overpasses equipped with rigid stays, spatial systems are employed in which reinforced-concrete beams, pylons, and rigid stays act together as a unified assembly. This system ensures force redistribution, reduced deflections, and stability under longitudinal and transverse loads.

Three analytical schemes are considered, each with average span lengths (without specifying a particular static scheme or accounting for the width of the monolithic transverse girders at the pylon level):

Reinforced-concrete beams. The primary load-bearing elements are reinforced-concrete beams and slabs of various types and sizes, selected according to the span lengths. Key data for the analytical schemes are as follows

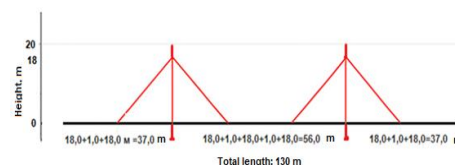


Fig. 1. Analytical Scheme No. 1 – Span Structure with Rigid Stays



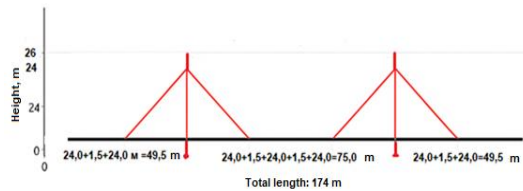


Fig. 2. Analytical Scheme No. 2 – Span Structure with Rigid Stays

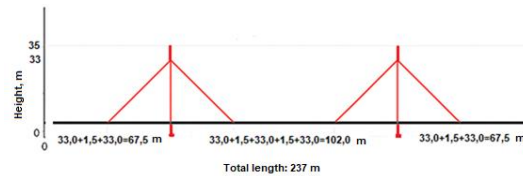


Fig. 3. Analytical Scheme No. 3 – Span Structure with Rigid Stays

- Scheme №1: Double-hollow slabs 18 m long, arranged into spans of 37.0 + 56.0 + 37.0 m. Slab depth is 0.75 m. Rigid stays are rigidly anchored to monolithic transverse girders measuring 1.0 × 0.75 m, provided every 18.0 m (see Fig. 1).

- Scheme №2: Prestressed ribbed beams 24 m long. Overall span arrangement is 49.5 + 75.0 + 49.5 m. Beam depth is 1.2 m. Monolithic transverse girders are 1.5 × 1.2 m in section. Rigid stays are rigidly anchored to these girders, provided every 24.0 m (see Fig. 2).

- Scheme №3: Identical beams 33 m long, with spans of 67.5 + 102.0 + 67.5 m. Beam depth is 1.5 m. Rigid stays are rigidly anchored to monolithic transverse girders measuring 1.5 × 1.5 m, provided every 33.0 m (see Fig. 3).

The carriageway width is 15 m, corresponding to four traffic lanes of 3.75 m each. In the transverse direction, there are 18 double-hollow slabs laid at 1.0 m centers for Scheme №1, or 8–9 beams laid at 2.1 m centers (including monolithic joints) for Schemes №2 and №3. The span structure rests on the transverse girders and supports with rigid stays, ensuring spatial stability and uniform force distribution.

Rigid stays. Rigid stays consist of steel tubular or box-section elements 24–35 m long, acting in bending, tension, and shear. Their inclination angle is approximately 45°. The stay design enables them to resist bending moments and transverse forces, transforming them into full-fledged stiff elements analogous to the diagonals of spatial trusses. This fundamentally distinguishes them from flexible cables [1], [6], [8]. In all schemes, there are four stays per pylon (two on each side). They are anchored at deck level to monolithic transverse girders, rigidly connected to the ends of the reinforced-concrete beams.

Pylons and anchorage. The pylons are A-shaped columns with a cross-section of 1.5 × 1.5 m. Their height above deck level varies by scheme:

- Scheme №1: 18 m
- Scheme №2: 24 m
- Scheme №3: 33 m

The anchorage zones where the stays connect to the pylons are reinforced and designed to transfer bending moments as well as accommodate possible horizontal loads (wind, seismic). The pylon carries all the forces from the inclined stays and transfers them to the supports and foundations, acting as a cantilever at an angle.

Interaction scheme. All three analytical schemes employ a three-span configuration with pylons located at the joints between spans. This arrangement optimally captures the forces in the stays and effectively controls deflections and the stress state of the span structure. The rigid stays, inclined at approximately 45°, together with the beams form a spatial lattice structure in which the primary load is redistributed among the bottom chords (beams), the diagonals (stays), and the columns (pylons), creating a stable geometry under external loads.

Theoretical foundations of the interaction between reinforced-concrete beams and rigid stays. General provisions. The combined action of reinforced-concrete beams and rigid stays is viewed as the interaction between a flexible horizontal beam and an inclined rigid element joined at a connection point. Unlike conventional systems with flexible stays, a rigid stay transmits not only axial force but also bending moment and possesses its own bending stiffness, leading to a substantially different force distribution in the span system [3],[8]. The system is analyzed as jointly working elements with differing stiffnesses. The beam is modeled according to classical bending theory, while the rigid stay is treated as an inclined elastic member with bending stiffness and an axial force.

Bending equation of the reinforced-concrete beam. For the span structure (the stiffness beam), the classical Euler–Bernoulli elasticity equation applies:

$$EI_b \cdot \frac{d^4 w(x)}{dx^4} = q(x) \quad (1)$$

where

- EI_b is the bending stiffness of the span beam;
- $w(x)$ is the vertical deflection;
- $q(x)$ is the distributed load.

The rigid stay is attached to the beam at $x=a$ and $x=b$, where a localized change in support reaction occurs and a bending moment may be introduced by the connected stay.

Governing equation for the rigid stay. Considering a rigid stay fixed at an angle α to the horizontal, its transverse bending under axial force N is governed by:

$$EI_v \cdot \frac{d^4 y(s)}{ds^4} + N_s \cdot \frac{d^2 y(s)}{ds^2} = 0 \quad (2)$$

where

- EI_v is the bending stiffness of the stay;
- $N(s)$ is the axial force at section s ;
- $y(s)$ is the transverse displacement along the stay's length $s \in [0, \ell]$.

This equation captures the effect of initial tension or compression on the stay's deformability. When rigidly clamped, the stay can transmit bending moments to both ends.

Boundary conditions and coupling. At the node connecting the beam and the stay, the following conditions are satisfied:

Compatibility of vertical displacements:

$$w(a) = y(0) \sin(\alpha) \quad (3)$$

Equilibrium of bending moment and shear force:

$$Mb(a) = M_v(0); \quad Vb(a) = V_v(0) \sin \alpha \quad (4)$$

where:

- Mb and Vb - are the bending moment and shear force in the beam;



- M_v and V_v - are the bending moment and shear force in the stay.

Thus, the system is mechanically coupled, and at the connection point the interaction of bending and axial forces is manifested.

Matrix Formulation of the Problem. For numerical modeling, it is convenient to use the matrix form of the system of equations, where the displacement and force vectors are combined into a global system:

$$[K] \cdot \{u\} = \{F\} \quad (5)$$

where:

- $[K]$ — the global stiffness matrix of the entire system, accounting for the flexural stiffness of the beam EI_b , the stiffness of the stay EI_v , as well as the axial force N ;
- $\{u\}$ — the nodal displacement vector of the system (including coupling conditions);
- $\{F\}$ — the vector of external loads.

At the connection node of the stay (on the beam and on the pylon), additional matrix constraints are introduced, corresponding to clamping conditions, moment continuity, and geometric compatibility.

Stress-Strain State (SSS) of the System. Force. Distribution in the beam. The reinforced concrete beam, operating as part of a system with rigid stays, is subjected to a combined action: uniformly distributed load $q(x)$, concentrated support reactions, and horizontal/vertical forces from the stays.

In the numerical formulation, combinations of variable loads were considered as prescribed in [SP 35.13330.2011], [ShNK 2.05.03–22], and as implemented in MIDAS Civil.

The following were specifically taken into account:

Permanent loads:

- self-weight of the beam and slab;
- weight of transverse beams, pylons, and stays;
- prestressing in the beams (TENDON model);

Variable loads:

- vehicular load (A14, NK-100 — both as uniformly distributed and lane load);
- temperature effects (from -20°C to $+35^\circ\text{C}$);
- seismic load (9-point intensity zone according to SP 14.13330 and ShNK);
- erection and service load combinations, including traffic in one or two lanes simultaneously.

Load Combinations Considered:

The following load combinations (for stress-strain analysis) were taken into account in the model:

- Permanent + short-term loads: $G+Q1G + Q_{1G}+Q1$;
- Permanent + temperature + seismic: $G+T+EG + T + EG+T+E$;
- Permanent + multi-lane traffic + $T + E$: the most unfavorable combination for the stay.

Load combinations were applied according to the regulatory framework, using reliability and combination factors (γ_f, ψ_i).

To describe the internal stress state in the beam section, standard expressions are used:

Shear force:

$$V_{(x)} = \frac{dM(x)}{dx} \quad (6)$$

Normal stresses in extreme fibers:

$$\sigma_{(x)} = \frac{M(x) \cdot y}{I} \quad (7)$$

where:

- $M(x)$ — bending moment at section xxx;
- y — distance from the neutral axis to the fiber;
- I — moment of inertia of the section.

Maximum stresses occur at mid-span as well as in the regions where the rigid stays connect (locations with abrupt stiffness changes and applied moments).

State of the Rigid Stay. The rigid stay is subjected to the following loads:

- Axial force N_v (from the self-weight of the span structure and prestressing);
- Bending moment at the connection point (depending on the stiffness and inclination angle);
- Shear force at the ends, resulting from the connection with the beam and the pylon.

The internal forces in the stay are determined from boundary conditions and equilibrium:

Axial force:

$$N_{(v)} = \frac{H}{\cos(\alpha)} = \frac{R_x}{\cos(\alpha)} \quad (8)$$

Bending moment (at the lower connection node):

$$M_{(v)} = -EI_v \cdot \frac{d^2y}{ds^2} \quad (9)$$

where

EI_v is the flexural stiffness of the stay, and the second derivative is evaluated numerically (or analytically in simplified models).

Influence of Stay Stiffness on the Beam's Stress-Strain State. The stiffness of the stay directly affects the redistribution of bending moments between the central span and the pylon zones. As EI_v increases, the following effects are observed:

- reduction of beam deflections in the spans;
- redistribution of bending moment from the mid-span toward the ends;
- increase in moments and stresses at the stay-to-beam connection point.

Specific Behavior of the Connection Node. The connection node between the beam and the stay is the zone of the highest concentration of moments and stresses. The following phenomena occur here:

- Bending moment M_b transferred from the stay;
- Shear force V ;
- the need for rigid anchorage of reinforcement in both the beam and the pylon.

To ensure reliable force transfer:

- monolithic transverse beams with reinforcement (analogous to diaphragms) are used;
- anchorage devices are designed as rigid fixings capable of resisting moments up to $80\text{--}100 \text{ kN}\cdot\text{m}$ [6], [9].

Modeling and Numerical Example. Selection of the Structural Scheme. It is important to note that the structural schemes No. 1 to No. 3 discussed above can, in principle, be implemented either as simply supported (discontinuous) or as continuous systems. Depending on the chosen static scheme of the overpass structure, the design spans will differ.

For the numerical analysis, Scheme No. 2 is considered — a three-span continuous system with rigid stays (see Fig. 4):



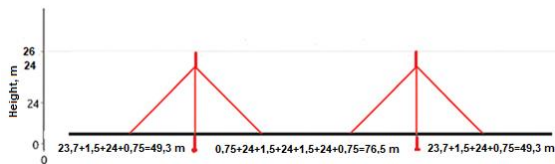


Fig. 4. Structural Scheme No. 2 — Continuous Span System with Rigid Stays

Design spans: 49.3 + 76.5 + 49.3 m. Bending moments and deflections are determined at the following cross-sections (horizontally, from the left abutment to the right): 0 m; 24.45 m; 49.95 m; 75.45 m; 100.95 m; 126.45 m; 151.95 m; 176.4 m.

Type of span structure: precast prestressed reinforced concrete beams, 24 m in length and 1.2 m in height;

- Roadway width: 15 m (4 lanes of 3.75 m), with 9 beams in the transverse direction;
- Pylons: A-shaped, 24 m high, with rigid anchorage of the stays at deck level;
- Rigid stays: 4 from each pylon, inclination angle — 45°, length of each stay — 24 m, cross-section — steel tube $\varnothing 325$ mm;
- Transverse beams at beam ends: cross-section 1.5×1.2 m, ensuring rigid connection between the stays and beams;
- Material: concrete class B40, reinforcement A500C.

Loads considered: A14, NK-100, self-weight, temperature effects, seismic loads (9-point seismic zone).

Computational Model. The model was built in MIDAS Civil using the TENDON function (for simulating prestressed elements) and element links between beam ends and the pylons via rigid stays. The beams and stays are modeled as volumetric beam elements, taking into account:

- flexural stiffness;
- prestressing;
- boundary conditions (rigid fixing at stay ends);
- real geometry and loading.

The system was solved using a linear static formulation, followed by refinement based on displacement results.

3. Results and discussion

Calculation Results. Bending Moments. The table below presents the bending moment values at **eight key points** along the span axis (including stay connection nodes, pylons, mid-spans, and abutments), under the following assumptions:

- $EI_v=0$ (flexible stay),
 - $EI_v=10^3, 10^4, 10^5, 10^6$ and $5 \cdot 10^6$ kN·m².
- Analysis Object:
- System: Three-span continuous — 49.5 + 75.0 + 49.5 m
 - Beams: Reinforced concrete, height 1.2 m, 9 beams across the width
 - Rigid stays: 2 from each pylon, inclination ~45°, spacing 25.5 m
 - Evaluation sections: 8 points along the axis (from 0 to 176.4 m)
 - Load type: Uniformly distributed load (symmetric case)

If you need the graph based on this table or its insertion into a Word file — I can generate it right away.

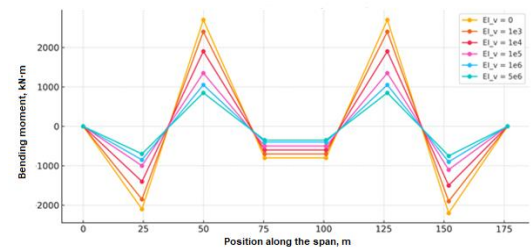


Fig. 5. Bending moment diagrams for Scheme No. 2 at various stay stiffness values from $EI_v=0$ (flexible stay) to $EI_v=5 \cdot 10^6$ kN·m²

Conclusions: As the stiffness of the stays increases, the negative bending moments near the pylons decrease by nearly a factor of 4. The positive moments in mid-span regions are also reduced to 25–30% of their initial values. The bending moment diagram becomes more uniform and flattened, resulting in lower reinforcement requirements and reduced internal forces. Deflection of the Span Structure. As a result of the numerical analysis, the following deflection values were obtained for Scheme No. 2.

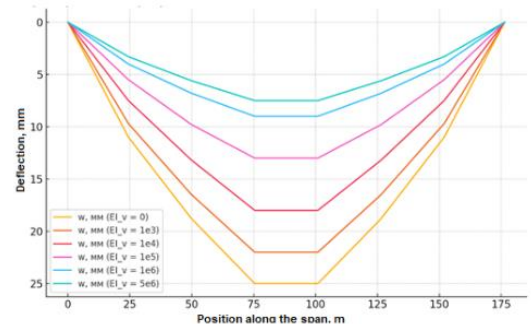


Fig. 6. Deflection graph for Scheme No. 2 at various stay stiffness values from $EI_v=0$ (flexible stay) to $EI_v=5 \cdot 10^6$ kN·m²

Conclusions: With increasing stay stiffness, deflections decrease by nearly 3.5 times. A clear **symmetry of deflection** is observed about the center of the span system (under uniform loading). Stays are effective as **spatial stiffness elements**, especially when $EI_v > 10^4 EI_v > 10^4$ kN·m².

Practical Recommendations for Designing Span Structures with Rigid Stays. Selection of Structural Scheme.

- Optimal span configurations:
- Ribbed beams: $2 \times 24 + 3 \times 24 + 2 \times 24$ m; $2 \times 33 + 3 \times 33 + 2 \times 33$ m
- Hollow-core slabs: $2 \times 18 + 3 \times 18 + 2 \times 18$ m

Design Parameters for Rigid Stays. Recommended stiffness range: $EI_v=10^4 \div 10^6$ kN·m² Geometry: tubular elements $\varnothing 325$ –426 mm, wall thickness 10–14 mm. Inclination angles — 45°, as optimal for structural efficiency. Stay anchorage — into transverse beams with a cross-section of at least 1.5×1.2 m



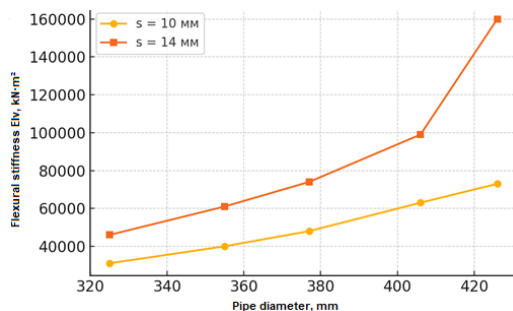


Fig. 7. Graph of Flexural Stiffness EIV vs. Pipe Diameter

From this graph (Figure 7), the following can be observed:

- At the same diameter, an increase in wall thickness significantly increases the flexural stiffness.
- In the diameter range of 325–426 mm and wall thickness of 10–14 mm, the values of EIV fall approximately within the range of $3 \cdot 10^4 \div 1.6 \cdot 10^5$ kN·m², which corresponds to the $10^4 \div 10^6$ kN·m² range used in design calculations.

Engineering Requirements for Structural Analysis.

- Load combinations must account for permanent and variable loads.
- Mandatory use of 3D numerical modeling (e.g., MIDAS Civil or LIRA-SAPR).
- Sensitivity analysis is required to assess the effect of changes in the stiffness of stays and main beams.
- Uniform load distribution across the beams should be ensured (9 beams for a carriageway width of 15 m).

Reinforcement and Structural Connections.

- Prestressed beams: 8 tendons with 24 wires Ø5 mm
- Transverse ties and diaphragms: every 6–12 m, especially near the stay anchorage points.
- Connection nodes between pylon and beam: rigid fixings with moment control.
- Recommendations for anchoring rigid stays to the pylon: anchorage height — not less than 24 m.

Seismic Resistance and Durability.

- Minimum concrete grade: B40; reinforcement: A500C.
- Resistance to temperature-induced deformations; installation of expansion joints for total bridge length exceeding 100 m.
- Corrosion protection of rigid stays and their joints.
- Structural reliability under seismic action up to 9 points.

Recommendations for Operation and Maintenance.

- Monitoring of deflections and forces through control sections (at pylons and mid-span zones).
- Consideration of deformations from prestressing effects.
- Inspection schedule: at least once every 5 years, using UAVs or robotic systems.

General Recommendations.

- Priority use of rigid stays under high-load conditions and where strict deflection limitations apply.
- Possibility to reduce beam cross-sections due to the load-bearing contribution of rigid stays.

- Efficiency: up to 15–25% concrete savings and 30–40% reduction in deflections.
- Architectural expressiveness can be achieved along with sound engineering optimization.

4. Conclusion

The use of rigid stays significantly increases the spatial stiffness of the system and reduces internal forces in the beams.

Selecting a stiffness of approximately $EIV \approx 10^5$ – 10^6 kN·m² achieves an optimal balance: moderate stay dimensions, efficient beam performance, and simplified reinforcement.

The system becomes less sensitive to further increases in EIV beyond 10^6 kN·m², which is important for engineering optimization and cost-efficiency.

Critical sensitivity range: 10^4 – 10^5 kN·m² — this is where the most rapid reduction in moments and deflections is observed. Further increases in stay stiffness lead to saturation of the effect.

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