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Seismic analysis of skewed bridges with soil-foundation flexibilities

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ABSTRACT

This paper describes several soil-foundation interaction models by which the equivalent linear spring constants for spread footings, pile footings, abutment backwalls, beams and wings are generated for the seismic analysis of highway bridges. For abutments or pile footings, these equivalent linear spring constants are transformed to a master joint through the Rigid Body Transformation method (RBT). The master joint is usually chosen at the center of gravity of the superstructure for abutments, and the center of gravity of the cap for pile footings to reduce the total number of degrees-of-freedom in the analysis and to take into account the geometric relationships among these spring constants. From the response spectrum analysis, the demand forces of these linear springs are calculated and compared with the corresponding structural components' capacities. The capacities include: abutment backfill passive pressure capacity, pile capacity, and footing bearing capacity. If the demand passive pressure of the backwall is greater than the allowable backfill capacity, then the equivalent linear stiffness of the backwall spring is revised and the next iteration is performed in the analysis. A numerical example is provided to show that the structure's natural periods and responses are strongly influenced by the abutment soil-foundation interaction model.

INTRODUCTION

Current AASHTO Specifications (1996) in Division I-A give specific methods for the structural analysis and design of bridges during earthquake loading. It is less specific with respect to the foundation modeling for the analysis. This is in part due to the complexities which are associated with the different foundation systems encountered in bridge structures in combination with the wide variety of soil types encountered in practice. In assessing the overall dynamic response of highway bridges, it is necessary to account for soil-foundation interaction effects. This paper summarizes several soil-foundation interaction models currently used by the Missouri Department of Transportation (MoDOT) for the seismic analysis and design of highway bridges. Based on these models, the equivalent linear spring constants of the spread footings, pile footings, and components of the abutment can be estimated using the soil boring data. Then the stiffness matrix of individual spread footings, pile footings, and abutments can be formulated using the Rigid Body Transformation (RBT) technique. The purpose of using RBT is to reduce the total number of degrees-of-freedom in the analysis and to take into account the geometric relationships among the spring constants. The response spectrum method associated with the iterative approach is adopted for the dynamic analysis. The purpose of the iterative approach is to find the effective linear stiffness in order to represent the nonlinear behavior of soil-backwall interaction. The effective stiffness of the backwall is adjusted if the calculated passive pressure of the backwall soil exceeds its passive capacity. This approach is also used in the soil-wing interaction. The capacities of the soil-foundation elements including the abutment backfill passive capacity, pile ultimate capacity, and spread footing bearing capacity, are also described in this paper for the analysis. A numerical example is presented to compare the current approach and the conventional approach which assumes 1) fixed foundations at the intermediate bents; 2) RBT is not considered; 3) only 2 stiffnesses corresponding to the abutment longitudinal and transverse directions are considered for modeling the abutments; and 4) one-half of the abutment backwall stiffness is allocated at each abutment and the resulting abutment backwall forces are doubled for design (Maroney and Chai 1994).

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SOIL-FOUNDATION INTERACTION MODELS

Spread footing spring constants

The equivalent linear stiffness matrix (Lam and Martin 1986) for spread footings and caps of pile footings is summarized as $[K] = \alpha * \beta * [K\ ]$ in which α and β are the foundation shape correction factor and the foundation embedment factor, respectively. Their values depend on the L/B and D/R ratios, respectively. L, B, D, and R are the footing length, width, thickness, and the equivalent radius of a circular footing which varies for different modes of displacement. The basic diagonal stiffness coefficients in $[K\ ]$ are three translational stiffnesses and three rotational stiffnesses. Note that the off-diagonal terms in $[K\ ]$ are neglected because the values of off-diagonal terms are small, especially for shallow footings.

Pile axial spring constants

The pile axial spring constants are evaluated based on the pile vertical ultimate capacity. The vertical ultimate capacity of piles in cohesive and cohesionless soils is first determined by the microcomputer program SPILE (Urzua 1993) using soil properties of soil layers from the boring data with consideration of groundwater table level. The program follows the methods and equations presented by Nordlund (1963, 1979), Meyerhof (1976) and Tomlinson (1985). For Cast-In-Place (CIP) friction pile in compression, the ultimate pile capacity, Q_u, is equal to the sum of the ultimate pile bearing capacity, Q_b, and the ultimate pile friction capacity, Q_f. Based on Q_b and Q_f, the pile axial bearing load (b) - axial deformation (z) curve and pile axial friction load (f) - axial deformation (z) curve can be estimated. The pile compliance is added to the rigid pile displacement. Then the total pile axial load-axial deformation relationship is determined. The pile axial load-axial deformation relationship is a nonlinear curve. Since the response spectrum analysis is a linear analysis method, the secant modulus stiffness (Lam and Martin 1986) of pile is used to represent the equivalent linear stiffness for the analysis. The secant modulus stiffness is defined as the slope between two points at which the axial loads are equal to zero and $\frac{Q_u}{2}$.

For steel HP pile bearing on rock, the ultimate pile capacity, Q_u, in compression is equal to the ultimate pile bearing capacity, Q_b. The friction capacity is not mobilized and the axial stiffness of steel bearing piles is assumed to be independent of soil properties and equal to $\frac{AE}{L}$ in which A is the cross-section of pile; E is the elastic modulus of pile; and L is the length of pile.

Pile lateral spring constants

The pile lateral spring constants are determined using the microcomputer program COM624P (Wang and Reese 1993) with a consideration of groundwater table level. COM624P was developed for use in the analyses of stress and deflection of piles under lateral loads. The theory upon which the program is based, is the widely-used p-y curve method which considers the nonlinear behavior of soils. The program determines pile deflection, rotation, bending moment, and shear by using iterative procedures in order to account for the nonlinear response of the soil. For a given soil profile, the pile lateral force-lateral deflection curve at the top of pile (pile head) can be obtained by applying incremental lateral forces at the pile head, the program then calculates the corresponding lateral deflections at the pile head. The material nonlinearity of pile is also considered in the program.

Since the response spectrum method is based on a linear analysis, the secant modulus stiffness is used to represent the equivalent linear stiffness. The secant modulus stiffness is defined as the slope between two points at which the lateral loads are equal to zero and $P(M_u)/2$, where M_u is the ultimate moment capacity of the pile; $P(M_u)$ represents the lateral load at which M_u is developed in the pile. The ultimate moment capacity of CIP pile or composite concrete-steel shell pile is based on the limit state of concrete strain $\varepsilon_c = 0.003$ and steel shell strain $\varepsilon_s = 0.015$. The ultimate moment capacity of steel HP pile is equal to the plastic moment, M_p, of the pile under constant axial load due to superstructure and substructure dead loads.

Abutment spring constants for backwall, beam, and wings

The abutment translational and rotational spring constants for backwall, beam, and wings are determined using estimated soil properties and the Wilson equations (Wilson 1988). The rotational spring constant of the backwall, beam, or wing can be obtained by using the computed translational spring constant.

Abutment rigid body transformation (RBT)

An abutment consists of many translational and rotational springs which represent the interaction between soil and backwall, beam, wings, pile caps, and piles as shown in Figure 1. To reduce the total number of degrees-of-freedom in the analysis and to take into account the geometric relationships among the spring constants, it is desirable to lump all the stiffnesses of these springs from "slave" joints to a "master" joint through a rigid body transformation (Cheng and Ger 1992, 1993). Any two joints on the rigid body (e.g. abutment) are constrained such that the deformation of one joint (the slave joint) can be represented by the deformation of the other joint (the master joint). Thus the degrees-of-freedom for the slave joint are transferred to the master joint, and the number of degrees-of-freedom in an abutment is reduced. RBT can also be applied to the pile footing by transforming all the pile springs and pile cap springs to an assigned master joint. Usually the master joint is placed at the center of gravity of the pile cap. The RBT takes into account the coupling effects between translational and rotational responses of skewed abutments. An in-house microcomputer program "RIGID" (Ger 1999) has been developed for the RBT calculation.

STRUCTURAL ANALYSIS USING THE ITERATIVE APPROACH

The force-displacement relationship at bridge abutments is a highly complex nonlinear problem affected by the abutment design. The following iterative technique associated with RBT can be used for the analysis of typical bridge structures by using the equivalent linear stiffness matrix of individual bridge components (i.e., abutments, spread footings, pile footing, etc.). The procedure is described in the following steps:

1. Calculate bridge components' (i.e., abutments, spread footings, pile footing, etc.) equivalent linear spring stiffnesses based on soil-foundation interaction models described previously.
2. Perform RBT to obtain stiffness matrix at master joints for abutments, pile footings, and/or spread footings.
3. Analyze the bridge by the response spectrum method and determine the forces at the master joints of abutments, pile footings, and/or spread footings.
4. Back calculate the force and displacement of each spring at abutments, pile footings, and/or spread footings.
5. Calculate abutment backfill pressure from the abutment backfill spring force from step 4. If the abutment backfill pressure exceeds the acceptable passive capacity of the abutment fill, reduce the abutment backfill spring stiffness to obtain the effective stiffness of the backfill spring. The effective stiffness of the backwall (spring constant) can be obtained by calculating the slope between the origin and the point which corresponds to the displacement of the backfill spring.
6. Check abutment pile forces against pile capacity. The pile interaction equation (AASHTO 1996) is used as the pile capacity. If the interaction equation for piles is greater than 1, redesign piles by adding more piles or use high yielding stress piles, etc. Recalculate the pile stiffness.
7. Check pile forces of pile footing. If pile axial force is greater than pile-soil ultimate axial capacity, Q_u, redesign pile footing.
8. Calculate spread footing soil bearing pressure distribution. If maximum soil bearing pressure is greater than the ultimate capacity of the soil, redesign spread footing.
9. If all the forces are less than or equal to the corresponding capacities mentioned in steps 5 through 8. Proceed to step 10. If not, go to step 2.
10. Observe the analyzed displacement at the abutment's master joint and take the appropriate following steps:
    (a) If the displacements exceed acceptable levels, then the abutment design is inadequate. Redesign the abutment and return to step 1.
    (b) If the displacements are acceptable, then the last abutment stiffness matrix is consistent with the abutment design.

CAPACITY CRITERIA USED IN THE ANALYSIS

Several capacity criteria used in the analysis are described here.

Abutment backfill capacity

Recently, abutment backfill passive capacity was studied using large-scale abutment tests at the University of California-Davis (Maroney and Chai 1994). The force-deformation relationship from the test indicated that the maximum soil passive pressure is about 287 KN/m^2. Caltrans utilizes an abutment capacity based on a soil passive pressure of 239 KN/m^2, amplified by about 50% to 369 KN/m^2 for earthquake loads. In this study, the abutment backfill passive capacity of 369 KN/m^2 is adopted.

Pile ultimate capacities

The ultimate capacity of the pile itself (not the pile-soil ultimate capacity, Q_u) is also used to check the pile forces. Since steel piles and CIP piles at abutments or pile footings are below the ground level, it is desirable to ensure that piles do not fail. Therefore a response modification factor of R = 1 is considered in this study although piles have good ductility capacity. The ultimate capacity of CIP pile or composite concrete-steel shell pile at a demand axial load is based on the limit state of ε_C=0.003 and ε_S =0.015. The ultimate capacity of steel H pile is based on the AASHTO 10.54.2

Soil or rock bearing capacity under spread footing

The ultimate soil or rock bearing capacities are based on AASHTO Specifications Division I, Section 4. The demand bearing pressures of the footing are calculated based on the finite element method. The procedure for this method is briefly described below. A typical footing is sketched in Figure 2 in which the footing is divided into many finite elements. Let y_0 and z_0 represent the initial principal axes of the footing. The soil is assumed to have no tensile capacity. Therefore the elastic modulus of soil is assumed to be zero for tension. When loads obtained from the response spectrum analysis are applied to the footing, some elements may separate from the soil, thus the instantaneous centroid location needs to be determined according to the compressive area of the footing (see Figure 2). The instantaneous centroid location C'(y'_{c0}, z'_{c0}) and rotation angle, β, are shown in Figure 2. The rotation angle β is the angle between reference axis y' which is parallel to the initial principal axis y_0 and instantaneous principal axis y. The sectional properties corresponding to the instantaneous principal y and z axes are calculated. EI_y, EI_z, and EA represent flexural rigidities in the y and z directions, and axial rigidity in the X (vertical) direction, respectively. The bearing pressure of each element shown in Figure 2 is computed by an incremental loading procedure. At each incremental step, the incremental loads including axial load, ΔP, moment in y direction, ΔM_y, and moment in z direction, ΔM_z, are applied to the footing and the footing sectional properties of , EI_y, EI_z , and EA, and the maximum bearing pressure of footing at that step are calculated. An in-house microcomputer program "SPREAD" (Ger 1996) was developed for calculating soil bearing pressures of spread footings under axial load and biaxial bending moments.

NUMERICAL EXAMPLES

An existing bridge as shown in Figure 3 was used to study the seismic response with respect to different soil-foundation modeling techniques. This bridge is a five-span prestressed concrete I-girder structure with integral pile cap abutments and concrete round column intermediate bents on pile footings. The total span length is 98.9 m with a skew of 45 degrees. The soil conditions at the site in general consist of submerged gray fine sand with some clay, loose to medium dense. Based on the original seismic design procedures, four wings were used at each abutment. All piles are cast-in-place with steel shells. This bridge is classified as an essential bridge with an importance classification coefficient (IC)=I, and an acceleration coefficient of 0.36g. Therefore the seismic performance category (SPC)=D is considered in the analysis and design. The original design of this bridge was based on the following conventional design criteria: 1) fixed foundations for all intermediate bents; 2) RBT is not considered; 3) only 2 stiffnesses corresponding to the abutment long. and trans. directions (Figure 1) are considered for the abutments; and 4) one-half of the abutment backwall stiffness is allocated at each abutment and the resulting abutment backwall forces are doubled for the design (Maroney and Chai 1994). Table 1 compares the abutment spring constants between the current MoDOT approach with the conventional approach

Table 1 - Abutment spring constants comparison

Current Approach by MoDOT	Conventional Approach
Use "SPILE" to determine pile axial spring constants Use "COM624P" to determine pile lateral spring constants	Pile axial spring constants are not considered Use "COM624P" to determine pile lateral spring constants

Use Wilson's equations to obtain backwall-soil and wing-soil stiffnesses	Use Wilson's equations to obtain backwall-soil and wing-soil stiffnesses
Consider spring constants (Figure 1) from: • backwall and beam cap (Fx, Fz, Mx, Mz) • beam piles (Fx, Fy, Fz, My, Mz) • wings (Fx, Mz) • wing piles (Fx, Fy, Fz, My, Mz) • wing pile caps (Fx, Fy, Fz, Mx, My, Mz)	Consider spring constants (Figure 1) from: • backwall and beam cap (Fx) • beam piles (Fy, Fz) • wings (Fx) • wing piles (Fy, Fz) • wing pile caps (not considered)
Use rigid body transformation (RBT) to formulate full stiffness matrix (6 x 6) at master joint	Sum individual element stiffnesses to obtain only 2 stiffnesses corresponding to abutment long. and trans.. directions

Four load cases are considered in an analysis. Case 1: apply seismic force in the bridge longitudinal direction; Case 2: apply seismic force in the bridge transverse direction; Case 3: 100% of Case 1 + 30% of Case 2; and Case 4: 100% of Case 2 + 30% of Case 1. Five conditions are studied here. They are

Condition 1: assume backfill of abutment #6 is subjected to passive pressure (e.g. bridge moves away from abutment #1). Backwall stiffness at abutment #6 is considered, but not at abutment #1. Flexible foundations are used with consideration of pile axial and translational springs for intermediate bents. Pile flexural spring constants are not considered at abutments or intermediate bents.
Condition 2: assume backfill of abutment #1 is subjected to passive pressure (e.g. bridge moves away from abutment #6). Backwall stiffness at abutment #1 is considered, but not at abutment #6. Flexible foundations are used with consideration of pile axial and translational springs for intermediate bents. Pile flexural spring constants are not considered at abutments or intermediate bents.
Condition 3: same as condition 1 but assume fixed foundations for intermediate bents.
Condition 4: same as condition 1 but with consideration of pile flexural spring constants at abutments only. Based on the soil boring data, the flexural stiffness of pile is calculated by the design charts (Lam, Martin, and Imbsen 1990) for submerged sand.
Condition 5: use conventional approach (e.g. one-half of the abutment backwall stiffness is allocated at each abutment; fixed foundations for intermediate bents; no RBT).

The natural period of this bridge for conditions 1 through 4 is about 0.37 seconds and the natural period based on condition 5 is 0.26 seconds. The difference is due to a very stiff abutment model in the conventional approach since only two translational stiffness coefficients corresponding to each abutment's longitudinal and transverse directions are considered and the other degrees-of-freedom are completely restrained (Table 1). Figures 4 and 5 show the abutments' forces parallel and perpendicular to the abutment beams and moments at the bottom of a typical column at the individual bents for conditions 1, 2, and 5 under seismic load cases 1 and 2, respectively. Comparing the envelope of conditions 1 and 2 with condition 5 in Figure 4 for load case 1 shows that the conventional approach is up to 45% higher than the abutment transverse force at the center gravity of the superstructure for the envelope of conditions 1 and 2. However, the abutment longitudinal forces have similar magnitudes. For load case 2 in Figure 5, the conventional approach is about 20% higher than the abutment transverse forces for the envelope of conditions 1 and 2. Figures 4 and 5 also indicate that the conventional approach's column moments are about 55% smaller than the envelope of conditions 1 and 2 for seismic load cases 1 and 2. This study indicates that the different modeling approaches used for conditions 1 and 2 versus those used for condition 5 yield a significant difference in the analysis results. The current modeling approach used by MoDOT in conditions 1 and 2 is believed to give more realistic results because the modeling techniques better reflect the bridge characteristics. From this study, the conventional approach overestimates the abutment forces and underestimates the column forces and pile footing forces at intermediate bents.

Figures 6 and 7 show the abutment forces parallel and perpendicular to the abutment beams and the moments at the bottom of a typical column at the individual bents for conditions 1, 3, and 4 under seismic load cases 1 and 2, respectively. Comparing conditions 1 and 3 shows that the column end moments of intermediate bents with fixed foundation are about 17% higher than those with flexible pile footings for load cases 1 and 2. Comparing conditions 1 and 4, it is noteworthy that the contribution of pile bending rigidities to the abutment stiffnesses is insignificant and the structural responses from both conditions are very close.

SUMMARY

Soil-foundation stiffness formulation is an important factor in seismic analysis and design. More accurate soil-foundation stiffnesses will result in more reliable bridge natural periods and responses. In order to simplify the analysis, equivalent linear spring constants are considered in the response spectrum analysis associated with the iterative approach for estimating abutment backwall and wing effective stiffness. To estimate abutment stiffnesses at the center of gravity of the superstructure or to formulate foundation stiffnesses at the center of gravity of the pile cap, the rigid body transformation approach is recommended to reduce the total number of degrees-of-freedom and to take into account the geometric relationships among the spring constants. Using conventional one-half of the abutment backwall stiffness approach for bridges with large skews and without RBT can result in significant error in the analysis. Using this conventional approach for modeling the abutment can significantly underestimate the intermediate bents' forces and can not adequately predict the abutment forces because of the restrained conditions assumed at abutments.

This paper also demonstrates that i) the column end moments of intermediate bents with fixed foundations are about 17% more than those with flexible pile footings and ii) the contribution of pile bending rigidities to the abutment stiffnesses is insignificant. Since this study is based on only one bridge, more parametric studies are needed to verify the trends and conclusions drawn in this paper.

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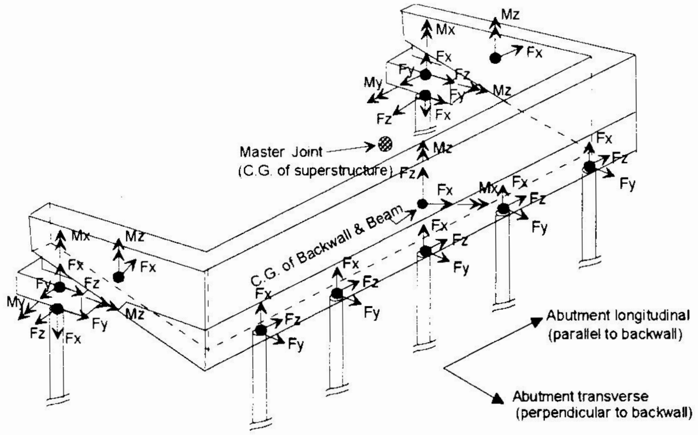


Figure 1 - Abutment spring constants considered.

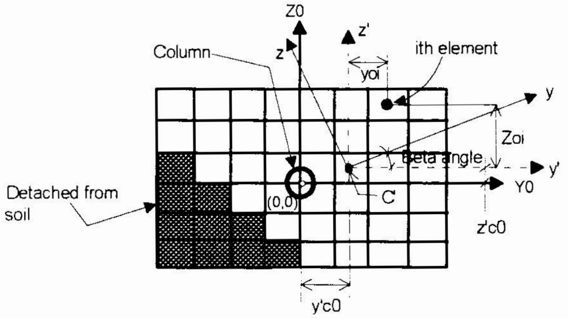


Figure 2 - Instantaneous centroid location, C', and instantaneous principal axes (y,z)

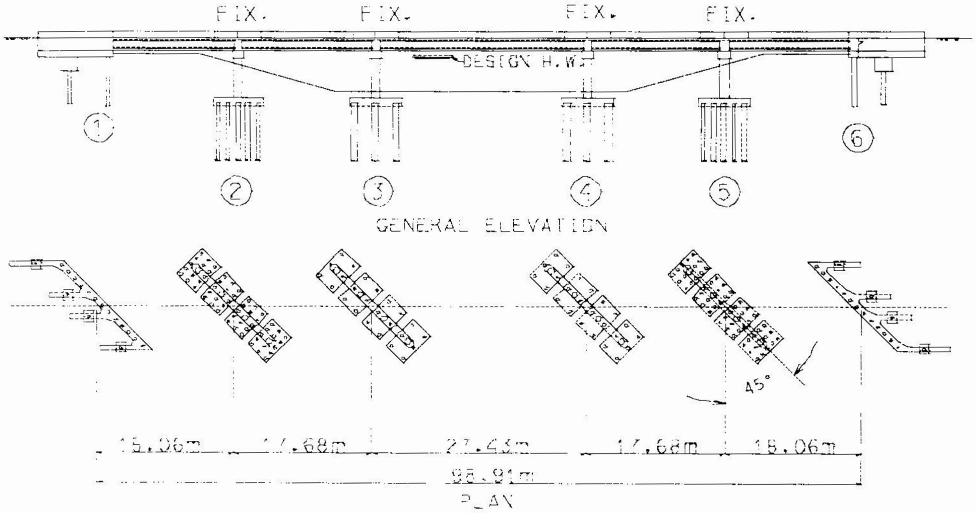


Figure 3 - Example: five-span prestressed concrete I-girder bridge

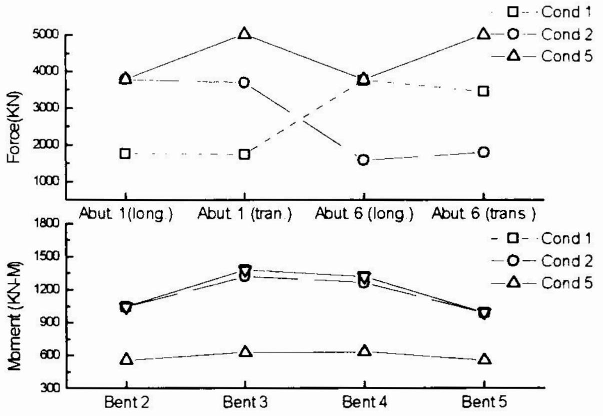


Figure 4 - Comparison of conditions 1, 2, and 5 for load case 1

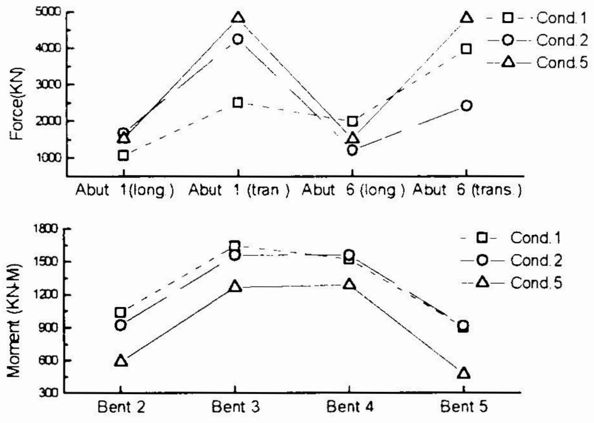
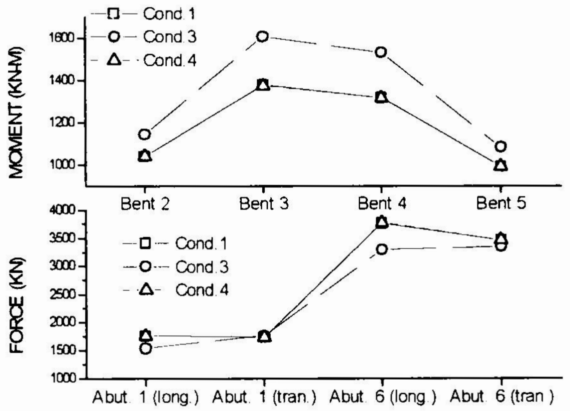
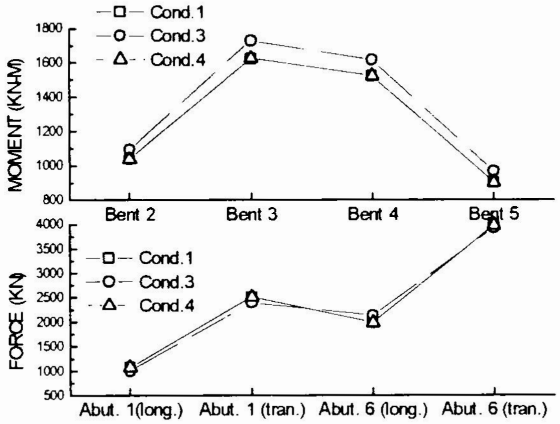


Figure 5 - Comparison of conditions 1, 2,





and 5 for load case 2

Figure 6 - Comparison of conditions 1, 3, and 4 for load case 1.

Figure 7 -Comparison of conditions 1, 3, and 4 for load case 2.