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Energy response in component tests

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ABSTRACT: The study of The University of Texas at Austin component tests load-deflection response provided valuable information about the controlling failure modes in the exterior and interior specimens. The energy response results obtained by integrating the hysteretic loops in the different locations of the tests critical regions showed the main sources of strain energy dissipation.

1 INTRODUCTION

The release of large amounts of strain energy stored in the tectonic plates through seismic-wave motions and crustal deformations is typical of the earthquake phenomena.

The response of reinforced concrete (RC) structural systems to seismic excitations requires that during the load-deformation process stable energy absorption-dissipation (ductility) response should be met.

Current research on RC structures under reversed cyclic loads involves studies on : (a) cracking patterns; (b) load-deformation response; and, (c) spread of yielding (bar strains).

The careful interpretation of the load-deformation hysteretic response may provide valuable information about the structure's response aptitude under large displacements.

2 The US-Japan Cooperative Programme

The US-Japan Cooperative Programme on Large-Scale Testing involved the test of a full-scale seven-storey RC building at the Building Research Institute (BRI), Tsukuba, Japan, and component tests both in the US and Japan (Wight 1984).

The data obtained through the extensively instrumented University of Texas at Austin (UTA) component tests shown in Figure 1, provided an unique opportunity to identify the leading failure modes in the exterior and interior specimens. These components correspond to the critical regions to be found at level Z2 of the BRI building.

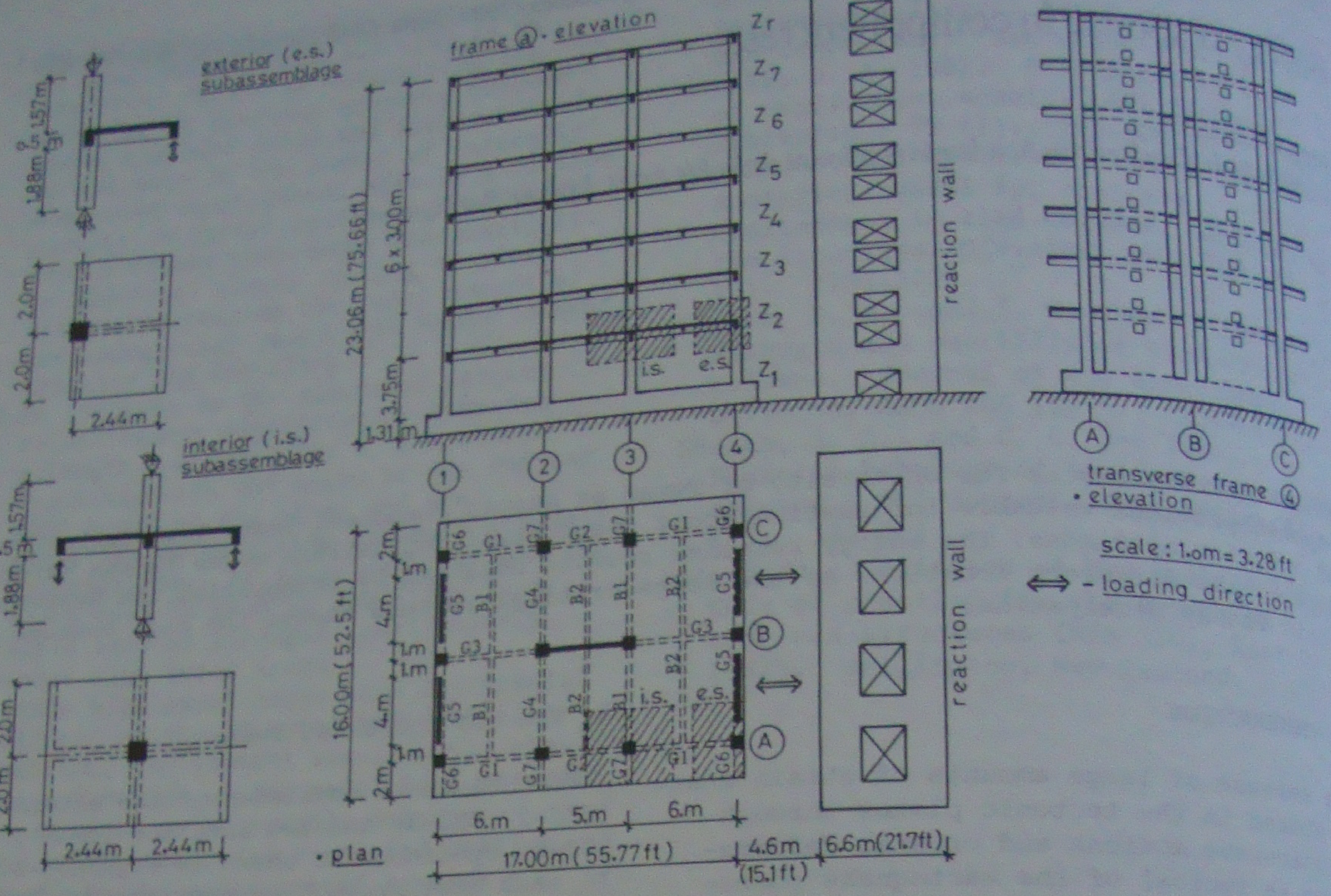
3 The UTA Component Tests

The UTA tests consisted of two exterior (USJ-2, USJ-4) and two interior (USJ-1, USJ-3) specimens as shown in Figure 1-a. In each test group, one specimen was built with the same reinforcement ratios as the BRI building (prototype tests : USJ-1, USJ-2) and the other specimen with nearly twice the beam and column reinforcement ratios (modified tests : USJ-3, USJ-4), as shown in Figure 2. Slab reinforcement consisted of two sheets of orthogonally placed no. 3 bars. Along the loading plane, the top and bottom bars were evenly spaced at 30.0 cm (12.0 in.) o.c.. On the orthogonal direction, the first two top and bottom bars adjacent to the column face were placed at 30.0 cm (12.0 in.) and then, onwards at 20.0 cm (8.0 in.) o.c..

The materials used consisted of 4.0 ksi (28 MPa) concrete and 60.0 ksi (420 MPa) reinforcement steel.

The specimens were loaded at the beam(s) tip(s) by hydraulic jack(s) that applied a prescribed displacement-control programme. The recorded data included (Bastos 1987) : (a) beam tip loads ; (b) beam tip displacements ; (c) longitudinal beam rotations ; (d) transverse beam twists ; (e) joint core distortion ; and, (f) bar strains.

The component tests were designed based on the weak beam-strong column concept. Consequently, the potential critical regions (plastic hinges) in test response were: (a) longitudinal beam rotation ; (b) joint core distortion ; and, (c) transverse beam twist. The relative importance of each plastic hinge mechanism depended on the type of specimen (exterior or interior).



a. UTA Components. b. BRI building and critical regions at level Z2.

Figure 1. US-Japan Cooperative Research Programme on Large-Scale Testing : UTA component tests and full-scale seven-storey BRI building, Tsukuba, Japan.

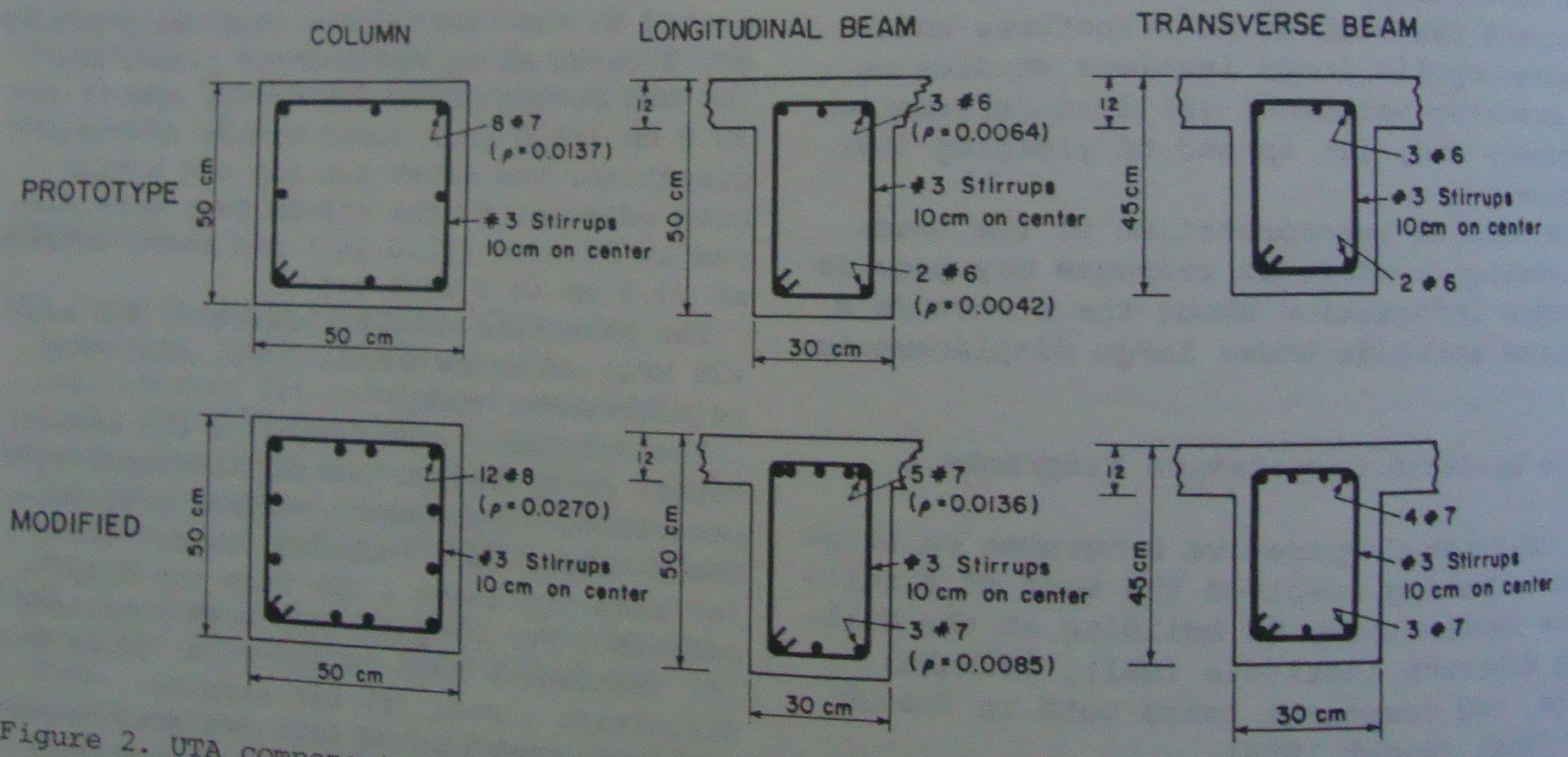


Figure 2. UTA component tests cross-section characteristics - prototype and modified subassemblage tests.

4 Assessment of Energy Response

The finite, closely bounded UTA tests provided an excellent opportunity to compare the external work created by the beam tip loads with the internal work (strain energy) being developed in the component critical regions. It is assumed that the kinetic energy term can be neglected because the external racking loads were slowly applied. Consequently, all the external work, W, was converted into strain energy, U :

$$W \cong U \tag{1}$$

In the UTA tests, the external input energy (IE) had to be dissipated through plastic hinging in the longitudinal beam (DE_b), joint core plastic shearing (DE_{jc}), and, transverse beam plastic hinging (DE_{tb}). It was assumed that the remaining specimen regions remained elastic (ex:column) and limited amounts of strain energy would be dissipated. Consequently, equation (1) can be rewriten as :

$$IE \cong DE_b + DE_{tb} + DE_{jc} \tag{2}$$

The total energy inputed (IE) was evaluated by integrating the area under the beam tip load-deflection response curve for two successive load increments (Bastos 1987). The number of recorded load stages for each test is shown in Table 1:

Table 1. Number of load stages in UTA component tests.

Test	USJ-1	USJ-2	USJ-3	USJ-4
No. of load stages	585	405	396	410

The history of the total energy being inputed into the exterior and interior tests is shown in Figures 3 and 4. The exterior prototype test USJ-2 that had anchorage failure was unable to store the large amounts of external work as observed in the other UTA tests, although the applied load histories were identical for all specimens.

The energy dissipated (DE) by the potential critical regions was computed by assuming a fixed gauge length ($\overline{GL}$) for the critical regions under study and by using the experimental values for the generalized forces (F) and displacements (d) :

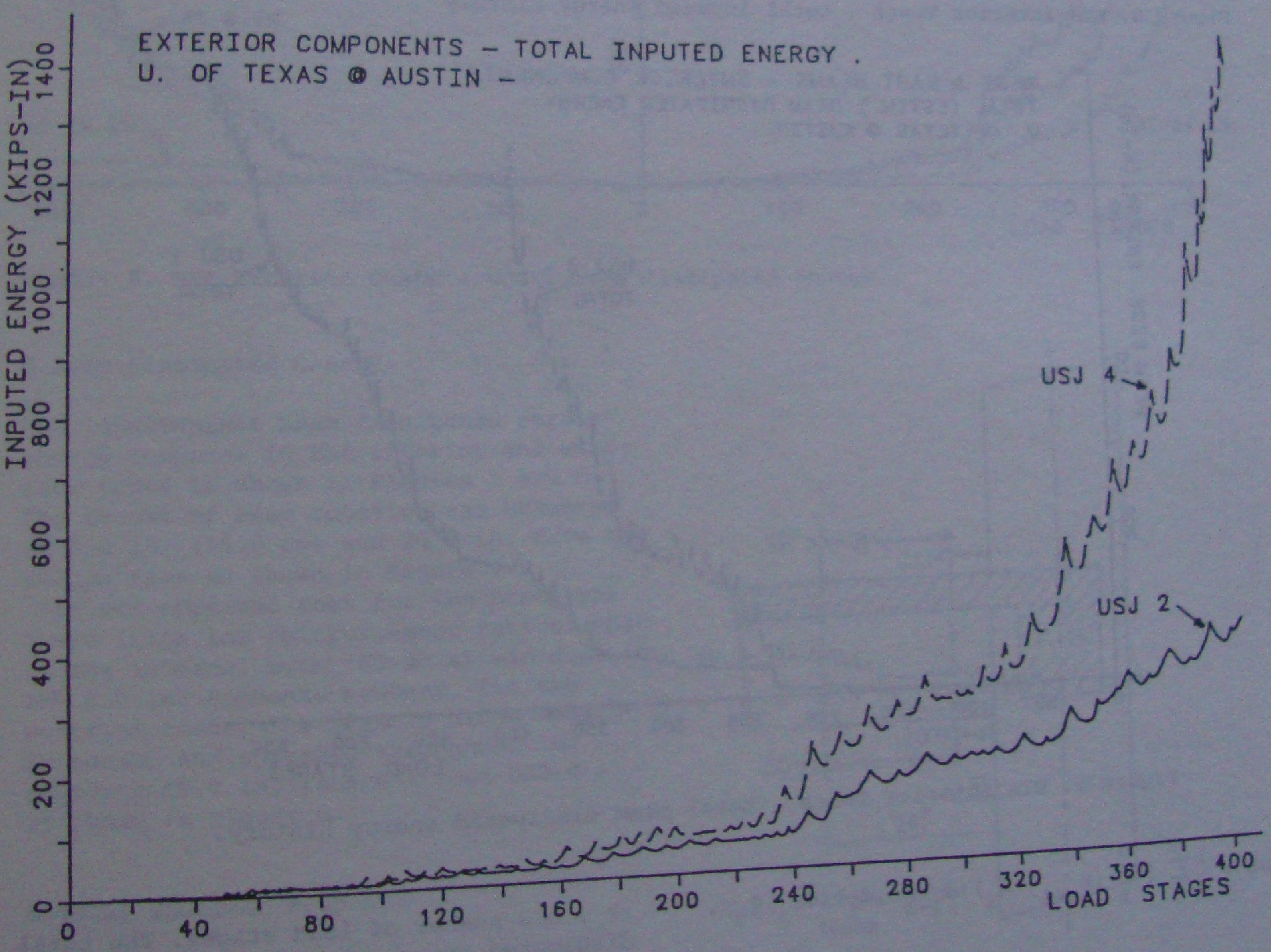


Figure 3. UTA Exterior Tests - total inputed energy history.

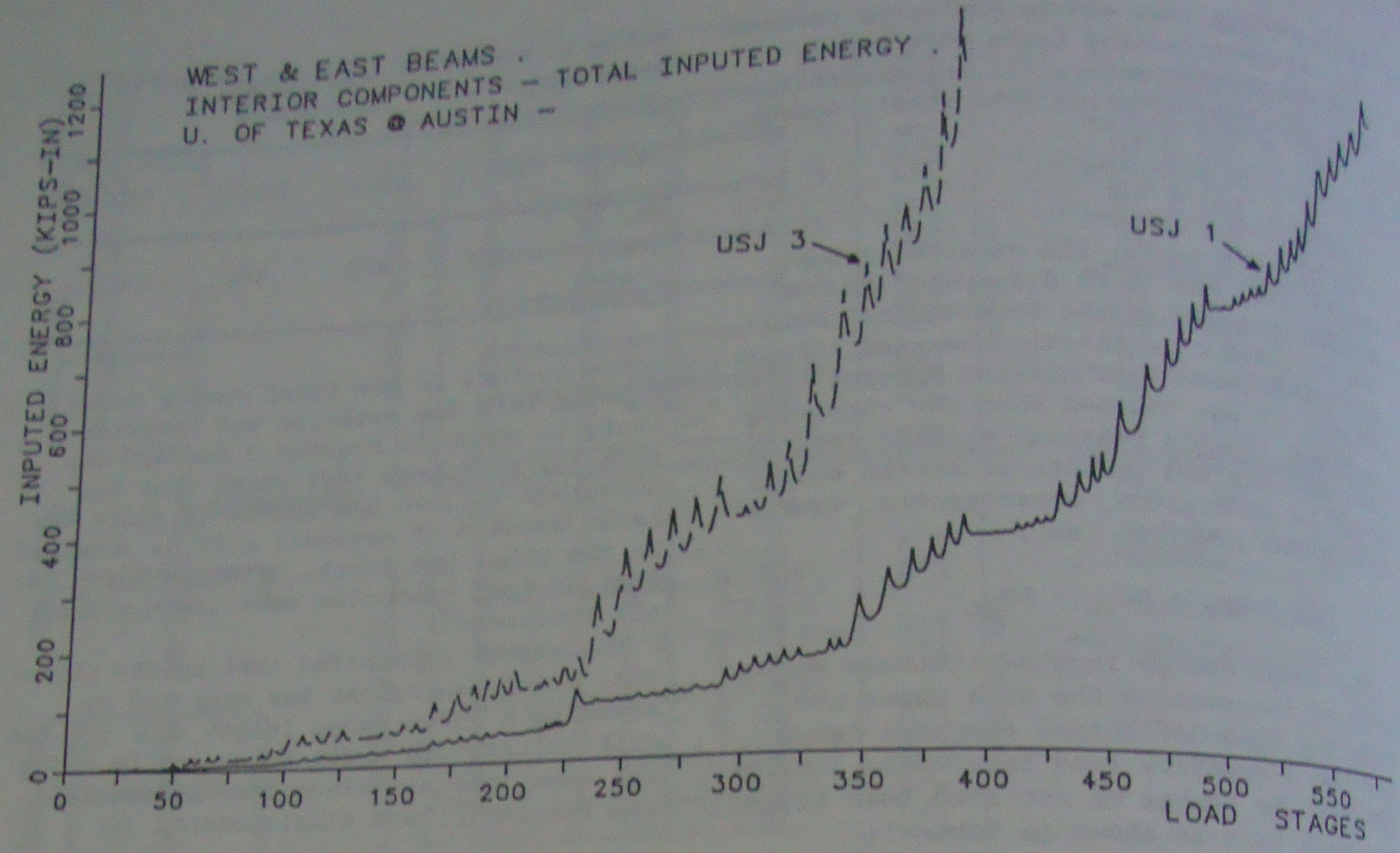


Figure 4. UTA Interior Tests - total inputed energy history

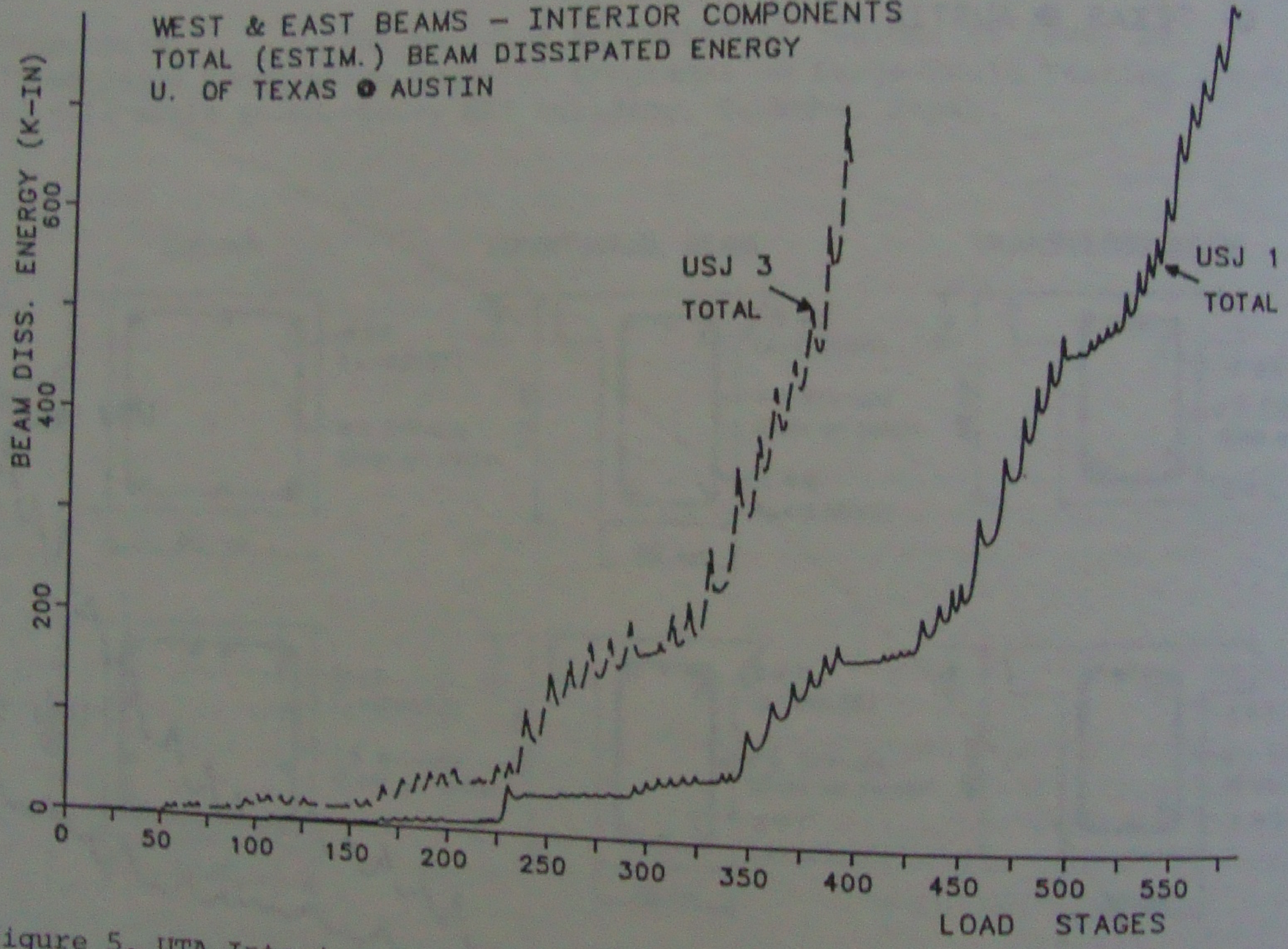


Figure 5. UTA Interior Tests - total beam dissipated energy history.

$$DE = \frac{1}{2}\sum_{j}^{m}\left[\sum_{i}^{n}(F_{i+1}+F_{i})(d_{i+1}-d_{i})(\overline{GL}_{i})\right]_{j} , \qquad (3)$$

where : m = number of discrete ($\overline{GL}$) segments ; n = number of load stages. The total dissipated energy was computed for the longitudinal beam plastic hinges and the joint core shear distortion.

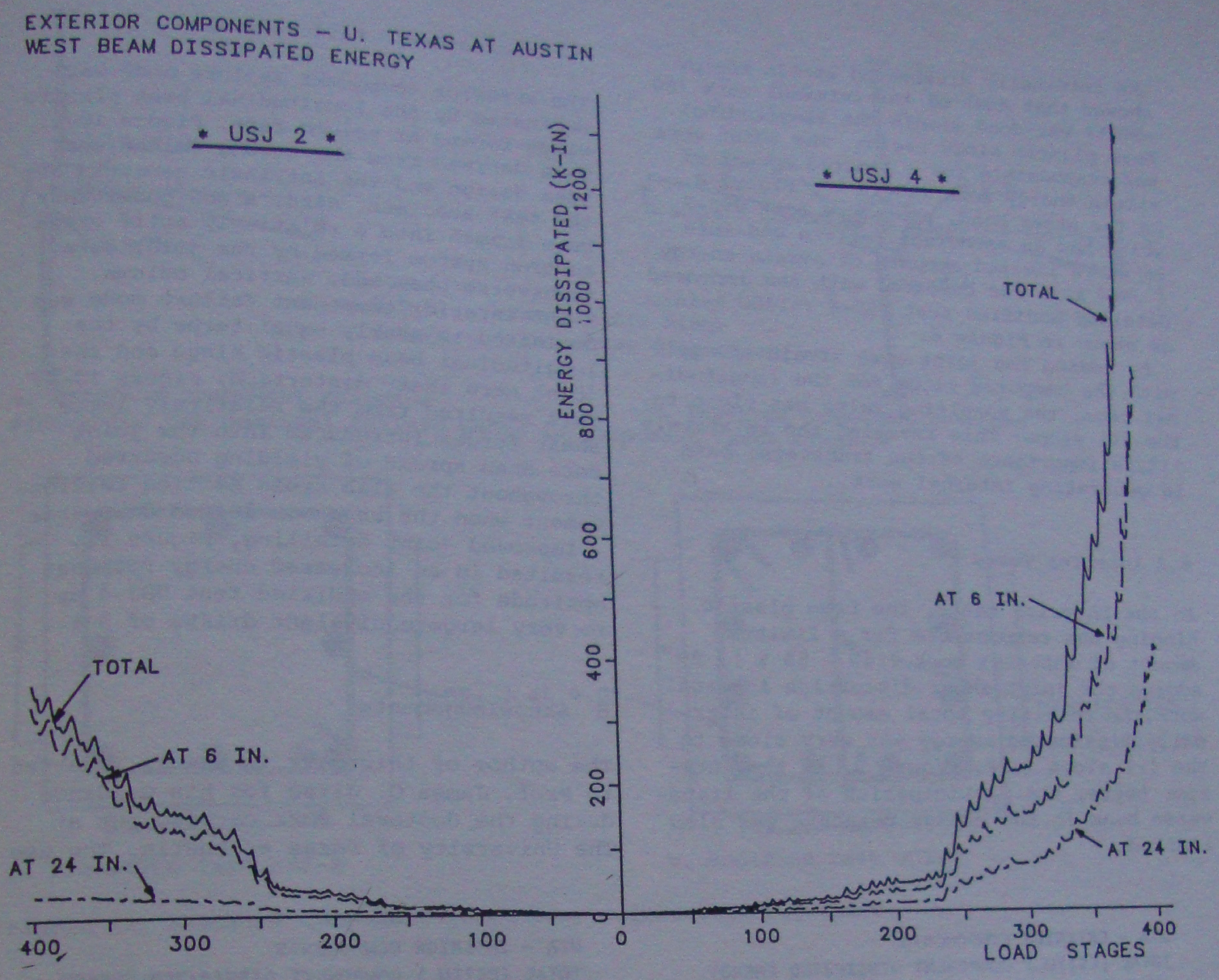


Figure 6. UTA Exterior Tests – total beam dissipated energy

5 Beam Dissipated Energy

The longitudinal beam dissipated strain energy response in the interior and exterior tests is shown in Figures 5 and 6. The amount of beam rotation was measured at 6.0 in. (15.0 cm) and 24.0 in. from the column face as shown in Figure 7.

It was observed that for the prototype tests (with low reinforcement ratios) most of the internal work (80-90 %) was done in the 6.0 in. segment. However, for the modified tests, the plastic hinge length increased and spreaded throughout the adjacent 18.0 in. length (test USJ-4) as shown in Figure 6.

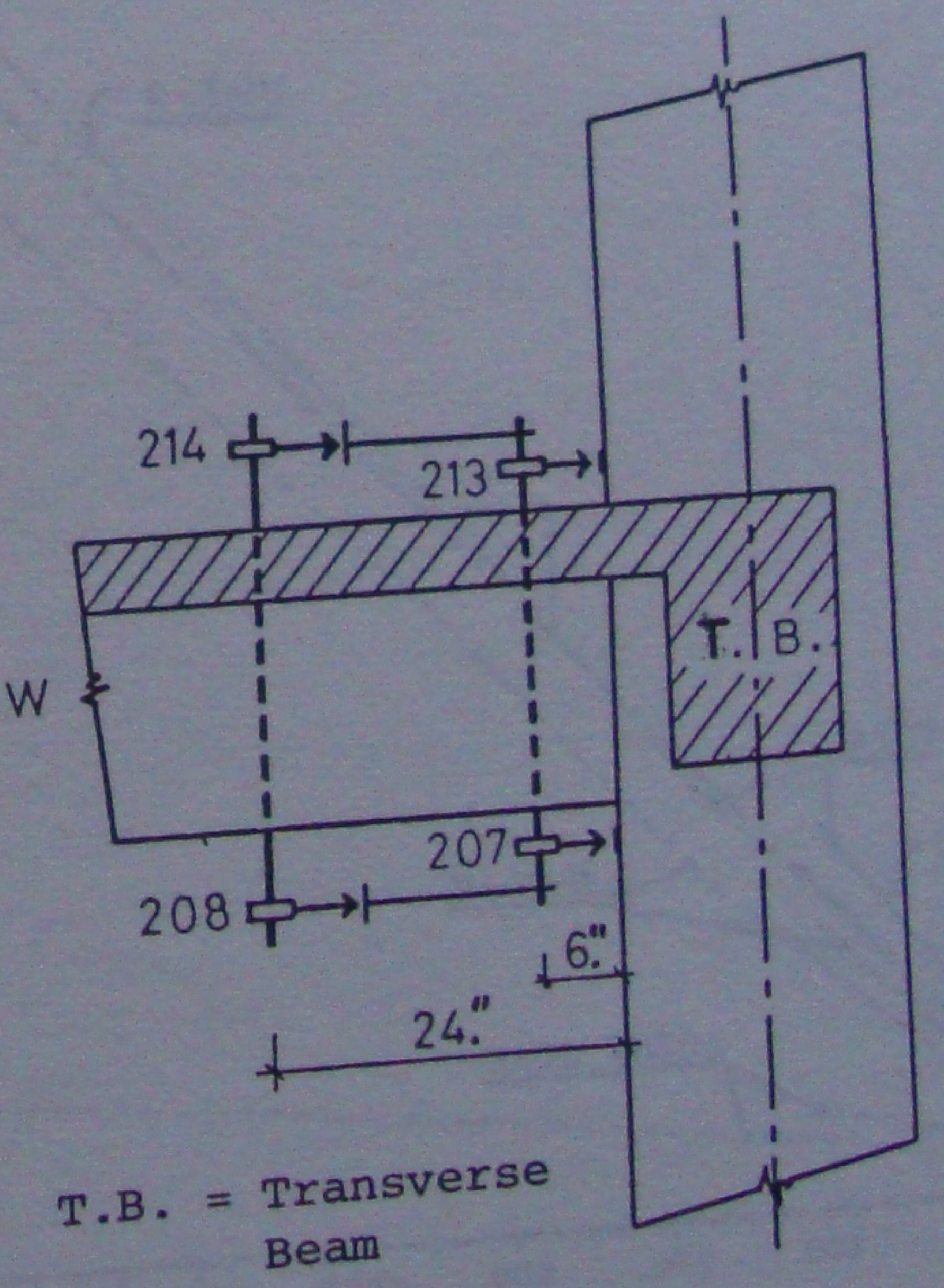


Figure 7. UTA beam rotion LVDT's location

6 Total Specimen Response

6.1 Exterior Tests

The comparison of the external work with the internally dissipated strain energy showed that most of the internal work (80 -90 %) was done within the longitudinal beam plastic hinge region. The joint core was responsible for a limited amount of strain energy work (20-10 %), Figure 8. On the other hand, prototype test USJ-2 which had an anchorage failure was able to store limited amounts of strain energy (~400 k-in)as compared with the improved detailed modified test USJ-4 (~1400 k-in), as shown in Figure 8.

By adding the joint core strain energy with the computed value for the longitudinal beam, the resulting value was close to the 1:1 slope. This revealed the relatively little importance of the transverse beam in generating internal work.

6.2 Interior Tests

In the interior tests, the beam plastic hinging was responsible for a limited amount of internal work (45 - 55 %). By adding the joint shear distortion internal work,the resulting total amount of internally dissipated energy was very close to the 1:1 slope line, Figure 9. In the interior tests, the participation of the transverse beam in the energy response was also limited.

7. Conclusions - Failure Modes

The exterior component failure mode was dominated by the longitudinal beam plastic hinge formed at column face, Figure 10-a. This derived from the strong column-weak beam design and the intrinsic geometry of the test specimen. Here, a non-continuous beam frames into a relatively stiff cross section system formed by the joint core, transverse beam and, vertical column.

The interior component failure mode was dominated in nearly equal terms by the longitudinal beam plastic hinge and the joint core shear distortion, Figure 10-b. This resulted from the relatively large shear forces introduced into the joint core when spread of yielding occurred throughout the slab cross section reinforcement when the beam was loaded downwards.

Improved joint detailing, Figure 11, resulted in an increased energy response aptitude for the modified test USJ-4 up to very large equivalent drifts of 5 %.

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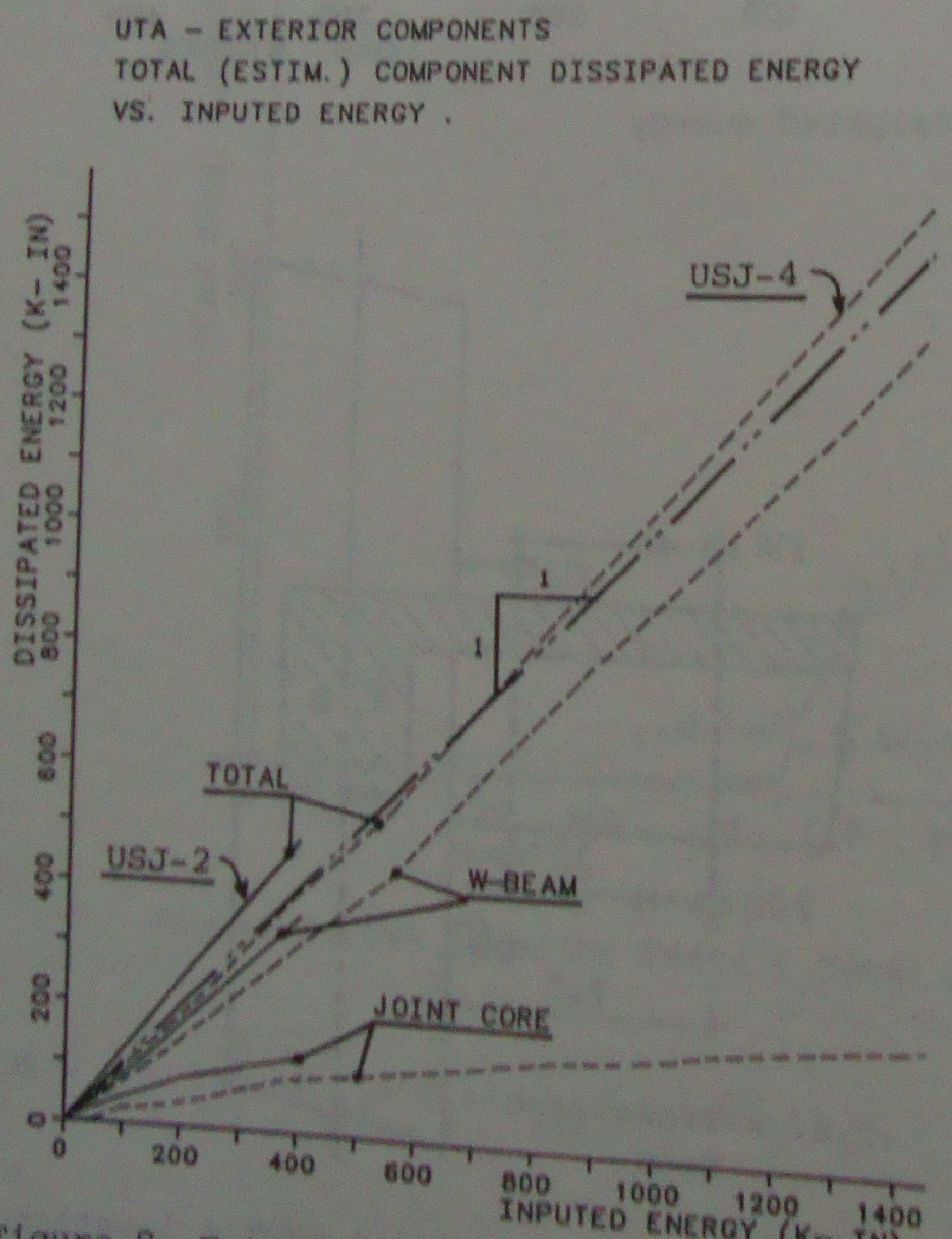


Figure 8. Exterior Tests Total Response

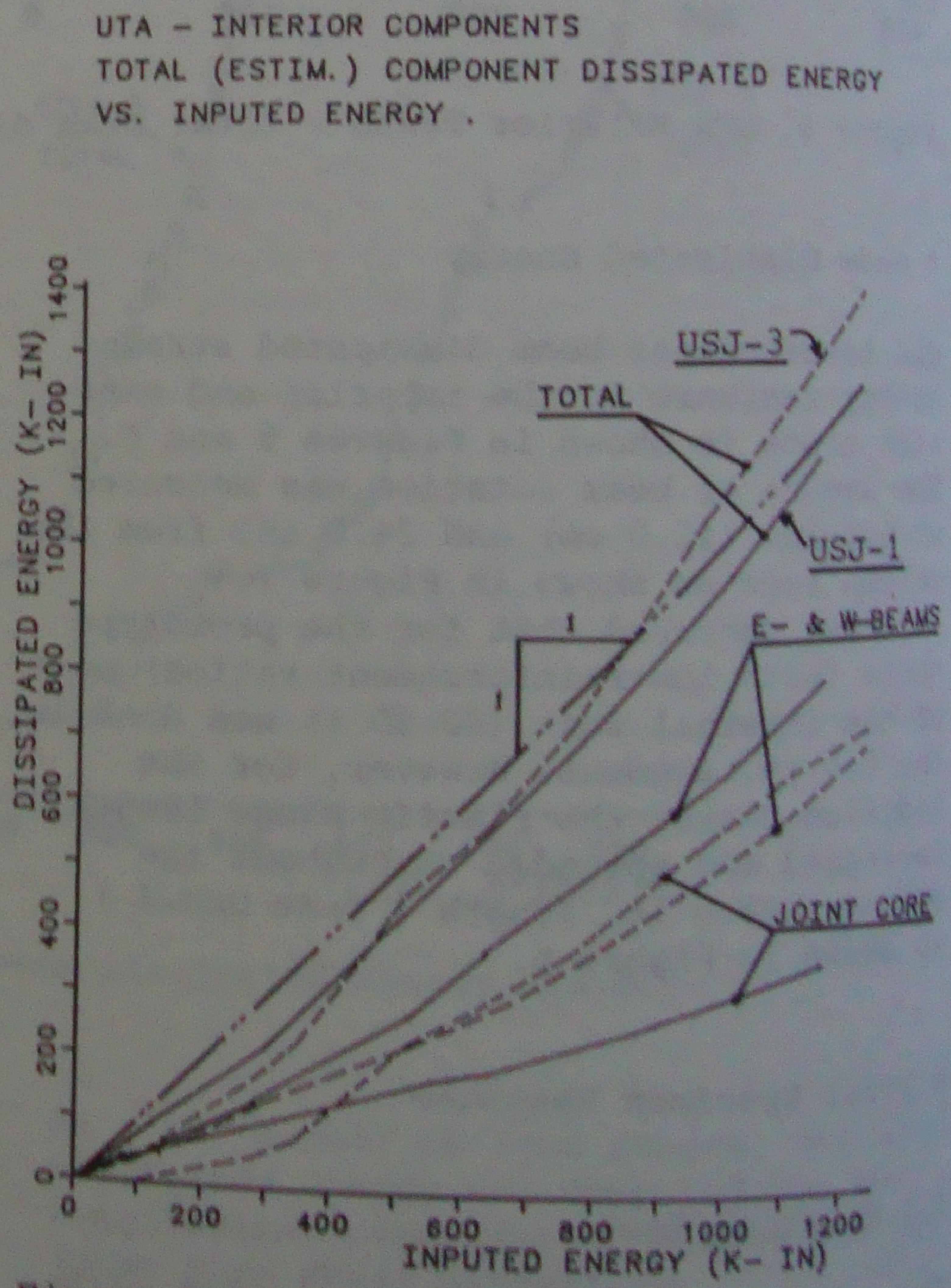
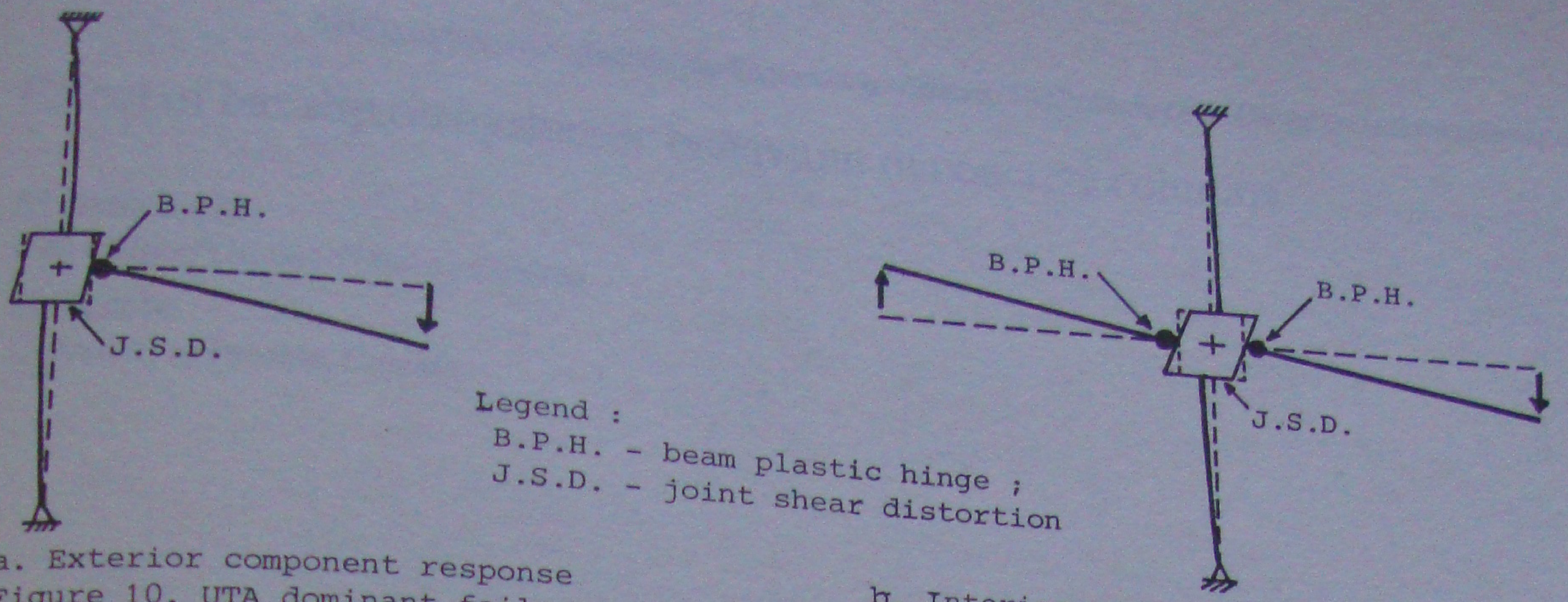


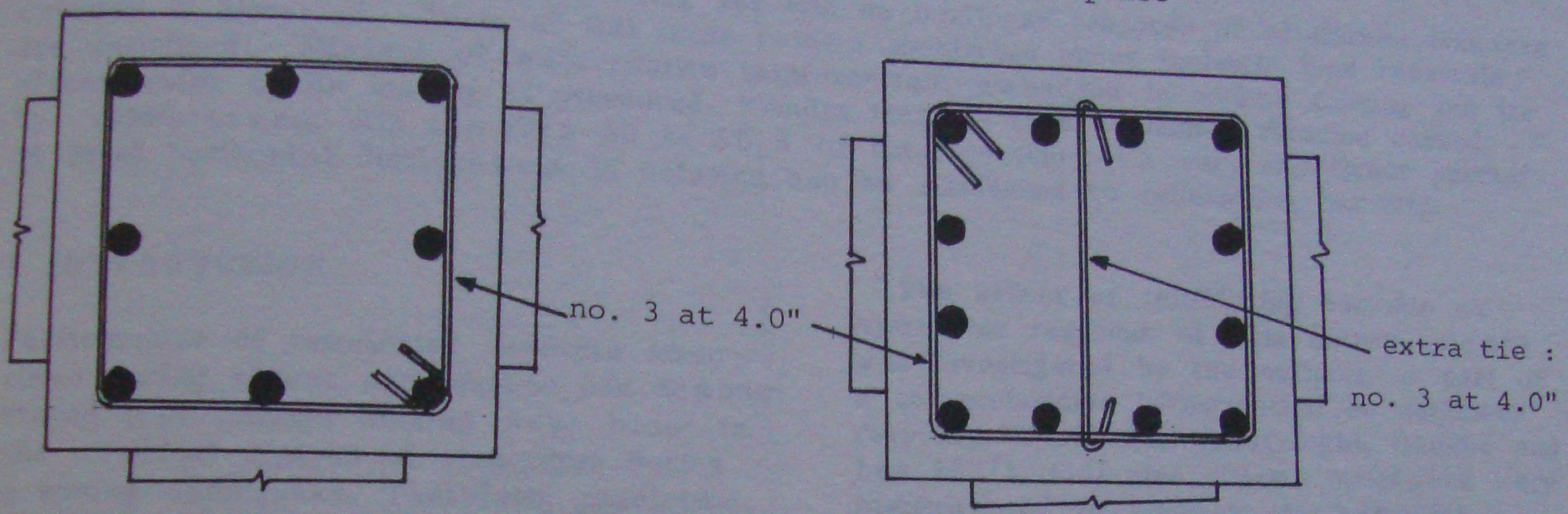
Figure 9. Interior Tests Total Response



a. Exterior component response

b. Interior component response

Figure 10. UTA dominant failure modes in component tests response



a. Prototype test USJ-2

b. Modified test USJ-4

Figure 11. Exterior component joint core reinforcement details

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