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AN ECONOMICAL STRUCTURAL SYSTEM FOR WIND AND EARTHQUAKE LOADS

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SUMMARY

An economical structural system which would mitigate undesirable vibrations due to earthquake loads is being developed. In this proposed system, the inherent hysteretic damping of the knee-brace-frame (KBF) with shear yielding knee is tapped to maintain the structural integrity in the event of a severe earthquake, while the frictional damping (in the form of Slotted Bolted Connection, SBC) in the brace of KBF is utilised to dissipate energy in order to meet the serviceability requirements during moderate earthquakes. As SBC dissipates energy without causing permanent damage, part of the strength required for serviceability design can be reduced by activating the SBC at an appropriate slip force. This would economise the material required for serviceability design.

INTRODUCTION

Generally, the design of buildings must satisfy two criteria. First, under frequently occurring low to moderate earthquakes, the structure should have sufficient strength and stiffness to control deflection and prevent any structural damage. Second, under rare and severe earthquakes, the structure must have sufficient ductility to prevent collapse. The commonly used structural systems such as moment-resisting frame (MRF), concentric braced frame (CBF), eccentric braced frame (EBF) and knee-brace-frame (KBF) are designed to resist the moderate loadings in the linear elastic range while the severe loadings through plastic hinges. The conventional MRFs and CBFs do not satisfy both criteria economically. A MRF is an excellent energy dissipating system, but it has to be designed with larger beam section in order to develop sufficient stiffness to prevent excessive drift. The CBF is much stiffer than the moment resisting frame with similar sections, but it has poor energy dissipating capability due to the buckling of the brace.

By connecting the brace eccentrically to the beam-column joint, EBF (Roeder and Popov, 1977, 1978) combined the good features of MRF and CBF. It dissipates energy through the development of shear hinges in the beam. As the beam is a principal member of the frame, the repair is very costly and difficult. The other system, KBF proposed by Balendra et al (1994), also combines the advantages of the MRF and CBF. In this system, the brace is connected to the knee, which is a secondary member, instead of the beam-column joint. The energy is dissipated through shear yielding of the knee while the brace is designed to prevent buckling. Since it is the knee that yields when severe earthquake strikes, the cost of repairing the structure is limited to just replacing the knee member only.

Various types of energy dissipating devices, utilising friction as means of energy dissipation, have been tested and studied by researchers (Pall et al, 1982, Constantinou et al, 1991, Aiken and Kelly, 1990) for wind and earthquake. These devices require precision workmanship and exotic materials for manufacturing and specialised training in installation. As a consequence, they are not widely accepted in engineering practice. The slotted bolted connection (SBC) proposed by Grigorian et al (1992) as energy dissipator represents an attempt to overcome the abovementioned shortcoming of these devices. The SBCs require only a slight modification of standard construction practice, and require materials that are widely available commercially.

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In this study, a SBC is incorporated into the brace of a KBF. The behaviour of the KBF with slotted bolted connection is investigated for its performance under seismic loads. One storey KBF with slotted bolted connection was tested using pseudo-dynamic test method (Balendra et al, 1987). The SBC in the brace was activated based on predetermined slip force. During severe seismic excitation, the knee was brought into inelastic action by preventing the slip as the drift approached the serviceability limit. Based on the experimental results, an analytical model for trilinear force-displacement behaviour of the brace with SBC is developed and incorporated as a subroutine in DRAIN-2D (Kanaan and Powell, 1973), a general purpose structural dynamic analysis program.

GENERAL CHARACTERISTICS

The diagonal brace of the KBF is connected to a knee element instead of a beam-column joint as shown in Fig. 1. The knee element is designed to dissipate energy under severe dynamic loading and therefore brace buckling or yielding of other members of the frame is prevented. A short knee member will yield in shear, while a longer knee yields in flexure. A KBF with knee designed to yield in shear has larger ductility than that designed to yield in flexural (Balendra et al, 1994). In this study, the KBF with shear yielding knee is investigated when the brace is incorporated with a SBC. In a SBC in Fig. 2, the elongated holes or slots in the main connecting plate are parallel to the line of loading. The main connecting plate is placed between two outer members. A friction lining pad is 'sandwiched' between each outer member and the main plate, and the lining pad always moves with the outer member. All the components are clamped together through bolts. Upon tightening the bolts, frictions develop between the contact surfaces of the lining pads and the slotted plate. When the tensile or compressive force applied to the connection exceeds the impending frictional forces, the slotted plate slips relative to the lining pads. Energy is dissipated by means of friction between the sliding surfaces.

The knee braced frame with slotted bolted connection retains the main features of KBF except the brace-column connection. The brace is connected to the column through a gusset plate with slotted bolted connection. When the brace force exceeds the impending frictional force of the SBC, the brace slips with respect to the SBC. The impending frictional force is always kept below the brace force required to yield the knee. In this way, the knee is always elastic when the SBC is slipping. The maximum slip distance of the SBC is governed by the slot length. Once the SBC hits the slot ends, the brace force builds up. The knee yields when the brace force exceeds the shear yielding capacity of the knee. Therefore, by altering the slot length of the SBC, the drift at which the energy dissipating capability of the knee to be activated can be controlled.

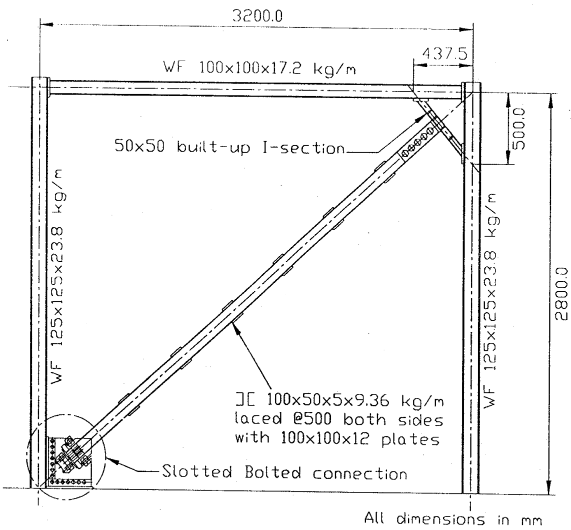


Fig. 1: Details of the test frame

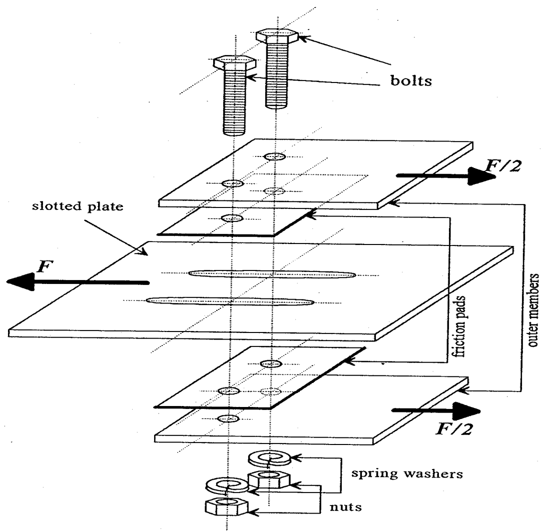
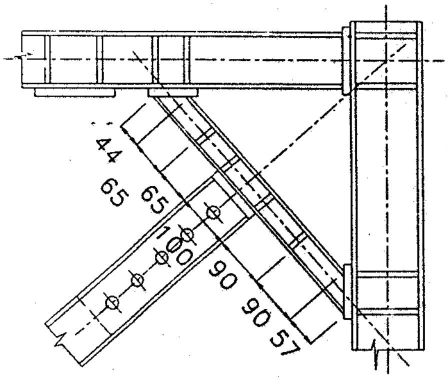


Fig.2: Basic set-up of the bolted connection

DESIGN OF THE TEST FRAME

The test frame is the same as the Test 2 specimen investigated by Balendra et al (1994) except for the inclusion of SBC. The beam and columns are wide flange sections 100 x 100 x 17.2 kg/m and 125 x 125 x 23.8 kg/m, respectively. These members are designed to remain elastic even when the knee member is loaded up to failure. The brace is designed to take cyclic loadings without buckling. It is made up of two C-channels (100 x 50 x 5 x 9.36) connected back-to-back with a 16 mm gap in between by 100 x 100 x 12 mm thick batten at 500 mm spacing. A built-up 50 x 50 mm I-section which have flange thickness of 6.0 mm and web thickness of 4.4 mm is used for the knee member. The length of the knee member is such it would yield in shear. The section chosen is also prevented from local and lateral buckling. The knee is designed to avoid premature shear buckling of the web by adding web stiffeners with maximum spacing of 90 mm. Figure 3 shows the details of the knee.



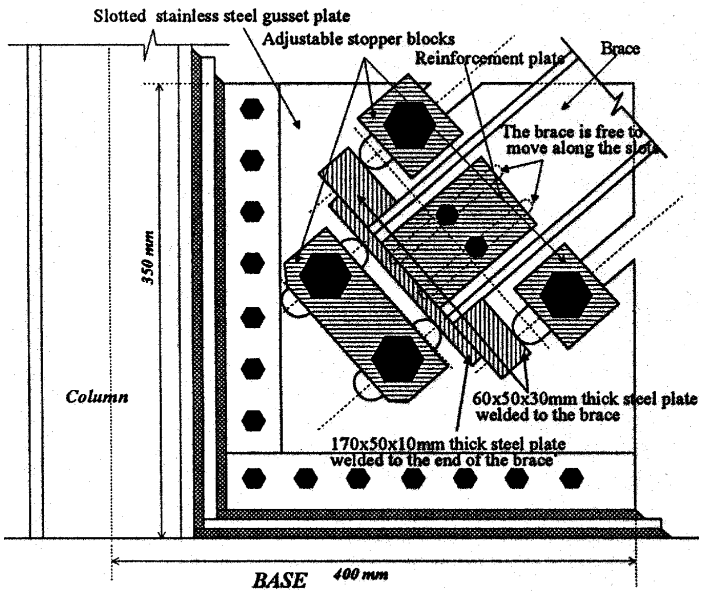


Fig.3: Details of the knee **Fig.4: Details of the modified SBC for the test frame**

The SBC is located at the lower corner of the frame, serving the connection between the brace and the column. The brace is connected to the column by being bolted to a gusset plate which is a 310 x 330 x 10 mm thick stainless steel plate with six elongated slots parallel to the brace as shown in Fig. 4. The gusset plate is bolted to the column flange and base for the ease of removing it for alteration. It serves as the main plate in the SBC. And the brace, which is made up of two C-channels, acts as the outer member in the SBC. Between each C-channel and the gusset plate there is a 3 mm thick brass shim inserted as the friction lining pad.

The gusset plate, C-channels and brass shims are bolted together through the two narrower slots in the gusset plate. In such a way, friction develops between the contact surfaces of the brass shim and the gusset plate. The amount of friction developed is proportional to the tightness of the bolts which in turn is proportional to the tightening torque. Thus, by adjusting the torque applied to the bolts, the desired impending frictional force can be achieved.

When the brace force exceeds the impending frictional forces, the brace slips together with the brass shim from the gusset plate. There are stopper blocks to control the maximum slip distance of the SBC. Although, theoretically, the maximum slip distance can be controlled by cutting the slot to desired strength, practically, it is very difficult especially for a tolerance of 1 mm. It can be seen from Fig. 4 that three stopper blocks are bolted to each side of the gusset plate. These blocks can be adjusted along the four bigger slots in the gusset plate. A 20 mm thick steel block, which acts as the contact point with the stopper blocks, is welded to the end of each C-channel. Thus, the gap between the steel block and the stopper blocks is the maximum distance the brace can slip with respect to the gusset plate. Once the steel blocks hit the stoppers, the brace force builds up and the knee yields when the brace force exceeds the shear yielding capacity of the knee.

EXPERIMENTAL SET-UP AND INSTRUMENTATION

For the dynamic testing of the frame, the pseudodynamic test is used. To study the behaviour of the brace and SBC, 4 linear strain gauges and a displacement transducer with an accuracy of 0.002 mm are installed at the locations shown in Fig. 5. The displacement transducer is used to monitor the distance the SBC has slipped. The strain gauges are used to record the strain level in the brace at every time step. From the strain readings, the slip force of the SBC can be deduced. The slip forces are particularly useful when comparing the experimental with the theoretical results using DRAIN-2D (Kanaan and Powell, 1973). They are to be used as the input for the brace tensile and compression strengths in DRAIN-2D (Kanaan and Powell, 1973).

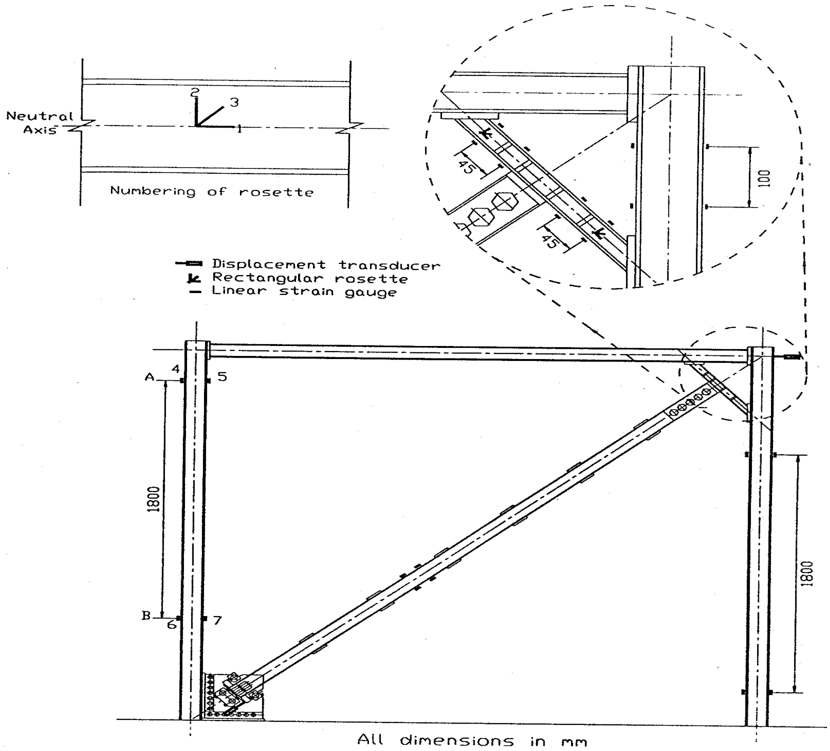


Fig. 5: Location of strain gauges, rectangular rosettes and displacement transducer

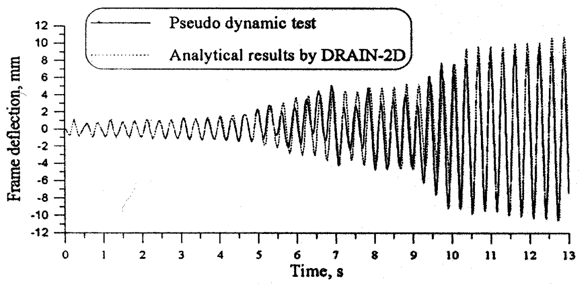
EXPERIMENTAL PROCEDURES AND TEST RESULTS

The determination of the impending frictional force in the SBC is the priority before any test is to be conducted. By trial and error, the bolts in the SBC is tightened with various torques in increasing order. For every setting, the frame is pulled and pushed statically, until the SBC slips. The maximum brace force when a particular torque is applied, is obtained by calculating the average of the 4 strain gauge readings in the brace. This process is repeated until the maximum brace force deduced is approximate 50 kN, which is less than the brace force of 57 kN at which the knee is expected to yield..

A free vibration test was performed before the elastic and inelastic tests to determine the coulomb damping in the frame. The free vibration test was conducted assuming the viscous damping of the frame is zero. If there is no coulomb damping, the plot of the restoring force versus frame displacement will be linear. On the other hand, the plot will show hysteretic behaviour if there exist some coulomb damping. The coulomb force is obtained by taking half of the different in force, F.

All the tests were monitored closely so that none of the members will yield before and after the SBC slips, that is, the brace force is kept below 57 kN. Before every test, the SBC was released and the frame was brought back to the position where the actuator load cell registers zero force. The SBC was then tightened to the prescribed torque. This is to ensure that there is no residual stress in the brace from the previous test.

In order to study the contribution from the inelastic behaviour of the knee to the energy dissipation capability of the frame, the test frame was stressed into the inelastic range using a sinusoidal base excitation with a frequency of 20 rad/s and an initial amplitude of 0.5 m/s^2. The amplitude is increased by 0.1 m/s^2 after every three cycles. A viscous damping of 2% of the critical damping is prescribed for the test. From free vibration test, the coulomb damping is found to be 450 N. The maximum slip distance of the SBC is restricted to ± 3 mm from the original position by the stopper blocks. The slip force of the SBC is adjusted to around 40 kN.



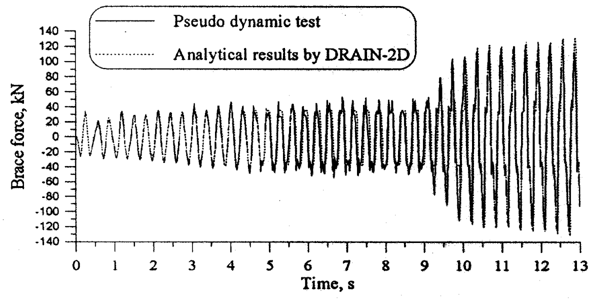
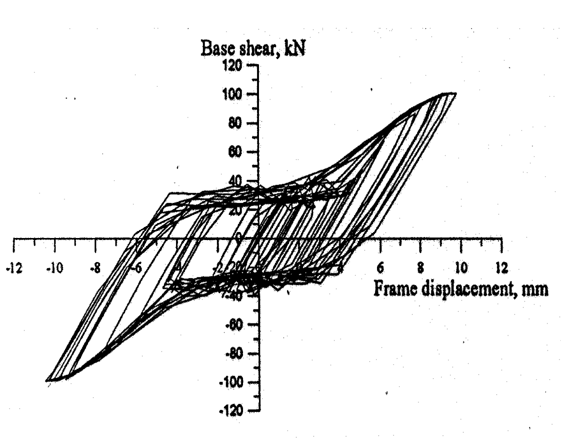


Fig. 6: Frame displacement-time history for inelastic test Fig.7: Brace force-time history for inelastic test

Figures 6 and 7 show the frame displacement-time history and the brace force-time history respectively. The SBC first slipped when the frame drift was 1/1500 (at time = 4.62 s) which is during sinusoidal ground excitation with amplitude of 0.9m/s^2. It can be seen from Fig.7 that the maximum brace force remained constant after that. At the drift of 1/560 (at time = 9.42 s), the brace hit the stopper blocks and the maximum brace force picked up. The corresponding peak ground excitation is 1.4 m/s^2. At the later part of the brace force-time history, the maximum brace force remained constant again. This was caused by the knee yielding. The test stopped when the drift was 1/280. The hysteretic curve for the test (see Fig. 8) is unpinched and no significant deterioration of strength and stiffness is observed. The hysteretic curve is made up of two parts. In the region between ±40 kN the SBC dissipated the energy. Outside this range, the knee dissipated energy (refer to Fig. 8). The slip force is reasonably constant and the brace force shot up when the SBC hit the 3 mm slip distance. The damaged knee is shown in Fig. 9. The peeling off of the paint from the web of the knee indicates the yielding of the knee. Figure 10 shows the hysteretic curve for the SBC.



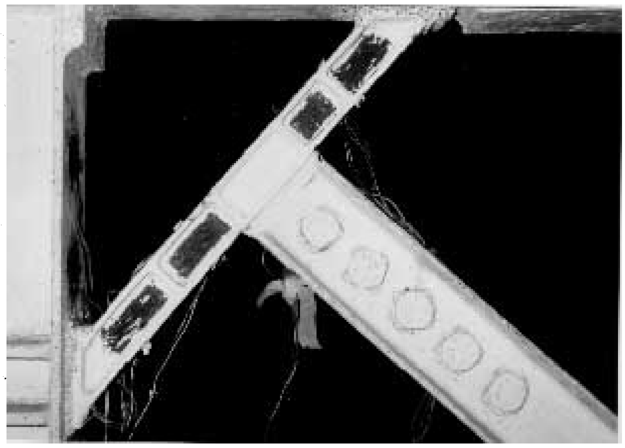


Fig. 8: Base shear displacement hyterisis for the elastic test Fig. 9: Tested knee

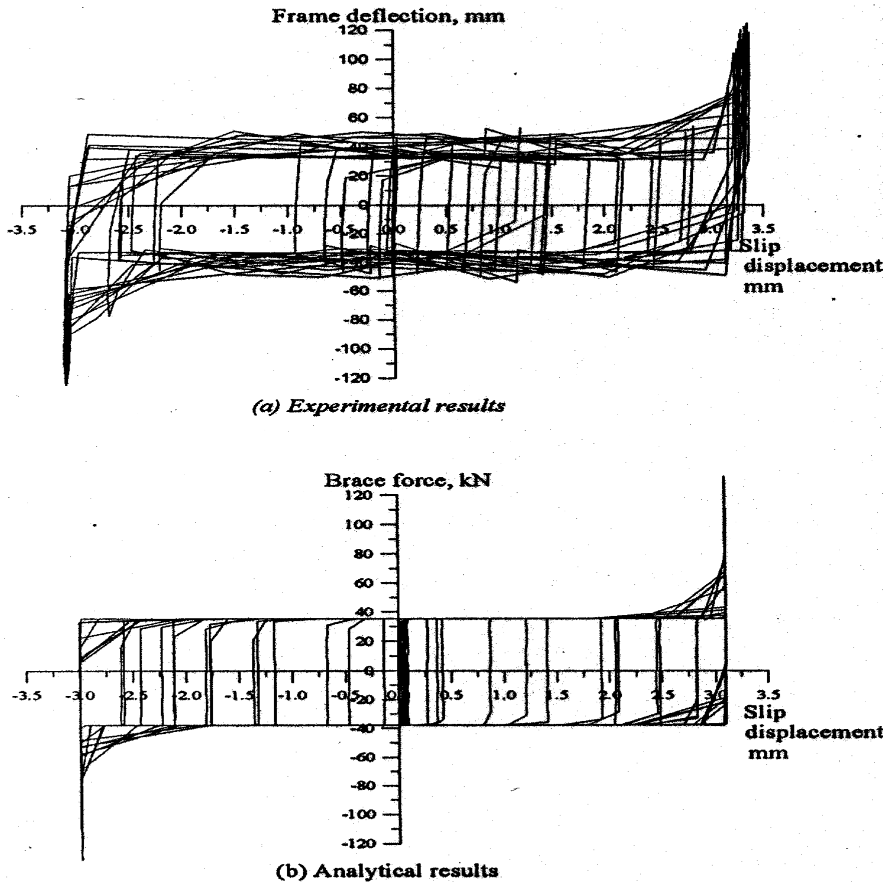
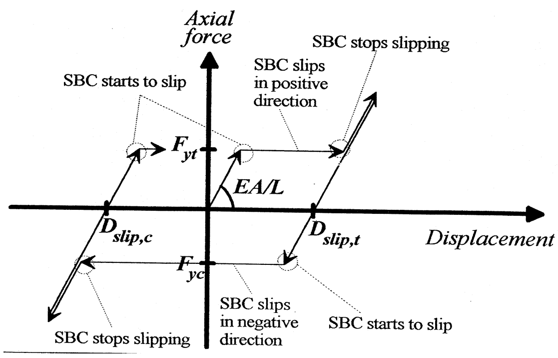


Fig.10 : Brace force-displacement hysterisis for the inelastic test

ANALYTICAL COMPARISON



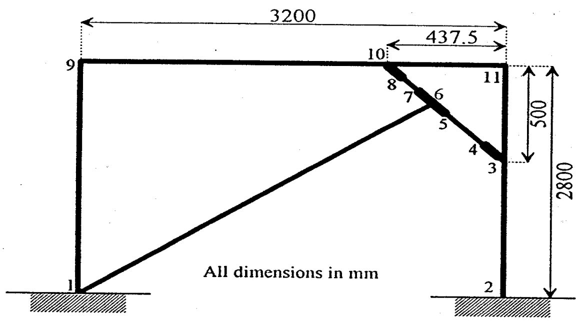


Fig. 11: Tri-linear truss model

Fig. 12: Analytical model for the test frame

DRAIN-2D (Kanaan and Powell, 1973) is used to compare the experimental results with analytical predictions. A subroutine for shear yielding element developed by Roeder and Popov (1978) is used to model the knee. For the modelling of SBC, a new subroutine was developed and added to DRAIN-2D (Kanaan and Powell, 1973). The SBC is assumed to be located at one end of a truss element which does not buckle. Thus, a tri-linear model as shown in Fig. 11 is adopted for the truss element instead of the ordinary bi-linear model. It is characterised by the parameters E, A, L, F_{yt}, F_{yc}, $D_{slip,t}$ and $D_{slip,c}$ which is the elastic modulus, cross section area, length of the truss, tension slip force, compression slip force, maximum slip distance in tension and maximum slip distance in compression respectively. The SBC slips when the axial force in the truss is F_{yt},or F_{yc}. When the SBC slips, the axial force remains constant at F_{yt},*or* F_{yc} depends on the direction at which the SBC slips. The axial force builds up again after the SBC hits the maximum slip distance $D_{slip,t}$ or $D_{slip,c}$.

The analytical model of the test frame is shown in Fig. 12. The beam and columns are modelled as beam-column element, the brace is modelled as a tri-linear truss element and the knee is modelled as a shear element. Rigid links are included in the model to account for the rigidity of the knee-beam, knee-brace and knee column joints. The stiffness of the rigid element is adjusted so that the elastic stiffness of the model matches the measured stiffness. Nodes 9, 10 and 11 are assumed to have the same horizontal displacement as the axial deformation of the beam is expected to be small. The mass is assumed to be lumped at any one of these nodes.

From the inelastic test results, knee yielding shear is estimated to be 60 kN and shear strain hardening ratio is 0.1. These values are used in the analytical model to simulate the inelastic behaviour of the knee. The tension and compression slip forces are required to model the tri-linear truss element. It can be seen from Fig. 10 that the maximum slip force is not perfectly constant. Therefore, an energy averaging method is used to quantify the slip forces to be input for the model, where the friction force is obtained by adding the total work done by the friction force in a particular direction and dividing it by the total distance the specimen travelled during the work done. The value thus obtained is the desired input slip force for the model. Accordingly, the tension slip force and compression slip force are found to be 35 kN and 38 kN respectively.

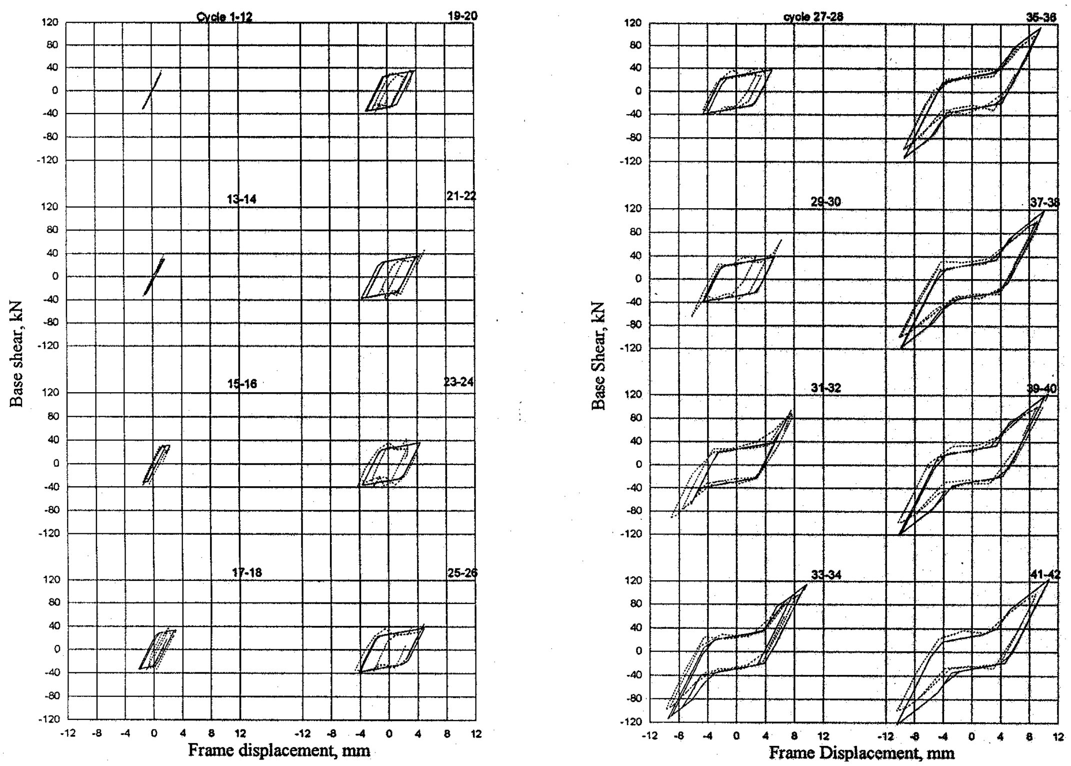


Fig. 13: Cycle by cycle comparisons between experimental and analytical hysteretic loops

The comparisons of the displacement-time history is shown in Figs. 6 & 7. Experimental and analytical results agree reasonably well. Some discrepancies are observed because of the difference in the actual slip force and the one used for modelling. From the comparisons of the experimental and theoretical hysteretic curves in Fig. 9, it can be seen that in the experiment the SBC did not always slip at same force whereas for the analytical model a constant slip force is assumed. The discrepancies can be seen more clearly in the inelastic test. As shown in Fig. 6, before the SBC is activated at 4.62 s, the experimental and analytical results agree very well. But between 4.62 s and 9.42 s when the SBC is governing the behaviour of the frame, the discrepancies is large. When the knee starts governing after 9.42 s, the experimental and analytical results agree very well again. Cycle-by-cycle comparisons for the inelastic test are shown in Fig. 13. The analytical curves agree reasonably well with the experimental curves.

CONCLUSION

From the large scale dynamic test results, the ability of the proposed system in dissipating energy at two different excitation level is proven. For this particular study, the SBC is activated when the frame drift is 1/1500, It ceases at the drift of 1/560 which is within the serviceability limit of the frame. When the frame is subjected to stronger excitation the inherent hysteretic damping of the KBF is tapped to maintain the structural integrity. The frame hysteretic loops are unpinched and with no deterioration in strength and stiffness. This implies that the system can dissipate a large amount of energy before failure. Further more, as the SBC dissipates energy without causing permanent damage, part of the strength required for serviceability design can be reduced by activating the SBC at an appropriate slip force. During severe earthquakes the damage is localised to the knee member, and thus retrofitting the structural frame will be easy and economical.

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