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The Paulay Years

by R. Park

Synopsis: An outline is given of the many significant and pioneering contributions made by Emeritus Professor Tom Paulay to the understanding of the behaviour of reinforced concrete and to the design of reinforced concrete structures for earthquake resistance. Particularly innovative has been his research into the design of structural walls for earthquake resistance, including the concept of the use of diagonal reinforcement in coupling beams. Other internationally recognised research described are his outstanding investigations into the mechanisms of shear resistance of reinforced concrete, aggregate interlock across cracks, behaviour of beam-column joints, and the capacity design and detailing procedures for structural walls and frames.

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FROM CAVALRY OFFICER TO UNIVERSITY PROFESSOR

Born in Sopron, Hungary on 26 May 1923, Tom Paulay was initially destined for a life in the Royal Hungarian Army. After attending a boarding school for military cadets in Sopron he entered the Royal Hungarian Military Academy in Budapest. On graduating he was posted as a second lieutenant to the same cavalry regiment in which his father served for many years.

One year later, in 1944, he faced the advancing Russian army in the Prypet Marches of the then Eastern Poland. At the age of 21, after mounting casualties, he found himself in command of a cavalry squadron consisting of 278 men and 308 horses. Action in Poland and later in Hungary, and months spent in various military hospitals, left him somewhat deaf, a feature remembered by his later colleagues and students.

After discharge from the army in 1946, with many other returned servicemen he joined the first year civil engineering class of 360 at the Technical University of Budapest. Describing this stage of his life, Tom Paulay has written that:

"The Technical University of Budapest after 52 days siege of the city was barely habitable. The fact that during the winter snow fell through large holes in the ceiling of the largest lecture room, did not interfere with the attraction with which brilliant lectures in engineering mathematics were followed. The professor wore two raincoats (his winter coat was buried under his house) and he wrote his equations on the blackboard wearing knitted gloves. Dozens of shallow graves all over the campus, where German, Russian and Hungarian soldiers had been hastily buried during the battle of Budapest, were daily reminders. They stifled any temptation to grumble about physical deprivations. Reliance by students on fellowship was a prerequisite to preserve sanity in the process of coping with hunger, the cold and the immense academic pressure.

The compromise between preserving free entry to the university and the greatly diminished immediate need for engineers in a totally collapsed economic system, resulted often in 75% failure rates at the end of the first year. While physical conditions improved slowly the political scene deteriorated dramatically. By 1948 Joseph Stalin and the Red Army imposed virtually full control over society by means of channelling the power into the hands of the Communist Party and its tool, the political police. For them to subdue within the campus an idealistic and hopeful but largely apolitical student body, was a formidable task. However, the outcome was inevitable. In 1948 Tom Paulay was one of the few who escaped from the Budapest equivalent of Rochester Hall (a Catholic hall of residence at the University of Canterbury), dissolved overnight by government orders. He made it across closely guarded forests to Austria and West Germany. Most of his friends, including his roommate, did not succeed. They spent some five years in a concentration camp".

In West Germany he enrolled at the Technical University of Munich but lack of financial resources soon terminated his attempt to continue civil engineering studies. For three years he occupied himself with international student relief activities, sustained by charitable organisations, in his new status as a stateless person. At this stage he began to teach himself English.

His next turn of fate favoured New Zealand. He was offered a scholarship by a small group of Catholic students from Victoria University of Wellington, New Zealand. As a result, in 1951 the International Refuge Organisation delivered Tom Paulay, his wife Herta and baby daughter to New Zealand. Two years later he completed a Bachelor of Engineering (Civil) degree at Canterbury University College. Before graduating he had brief periods of work experience as a maintenance labourer with New Zealand railways and as a labourer in woolstores. After completing BE (Civil) he worked for eight years as a structural engineer with a firm of consulting engineers in Wellington, where his ability and instinct for structural design became clearly evident.

In 1961 he joined the Department of Civil Engineering of the University of Canterbury as a Lecturer. There his main teaching interest was the application of engineering fundamentals to creative structural design. He proved to be a gifted and popular teacher. Encounters with students in the classroom were a prime source of joy to him. The students responded with enthusiasm, in spite of the high demands placed on them, and profited greatly from the experience - a very fortunate generation of students indeed. At the urging of the then head of department he embarked on research work in 1964 which led to a PhD degree in 1969. Progressing through the steps in the academic ladder, in 1975 he was appointed to a person chair (professorship) in civil engineering at the University of Canterbury.

He has maintained a continued interest and intense involvement in research at the University of Canterbury during the last thirty years. Although his first technical paper was published in 1967 when he was age 44, he has published 100 publications since that date, comprising 3 books, 9 book chapters and parts of seminar volumes, 58 papers in refereed journals and 30 papers in conference proceedings (see the attached list of publications by T Paulay). His publications have had a major impact on the seismic design of concrete structures and have been recognised by numerous awards and prestigious appointments both in New Zealand and overseas.

In 1983 he was elected to Fellowship of the Royal Society of New Zealand and in 1987 to Honorary Membership of the American Concrete Institute, the 23rd non-American so honoured since 1926. His services to civil engineering were marked by the Professional Commitment Award of the Institution of Professional Engineers New Zealand in 1985, and by being made an Officer of the Order of the British Empire in 1986. He has also received honorary doctorates from the Swiss Federal Institute of Technology and the Technical University of Budapest. He retired from the University of Canterbury in 1989 after 28 years of extraordinary service and achievement. Although retired he has maintained strong ties with his colleagues, attending most days to work in his study and to talk with staff, students and visitors at the University of Canterbury. He has also kept a high international profile, becoming the President of the International Association for Earthquake Engineering in 1992.

RESEARCH

Tom Paulay's research during the last thirty years has had a profound effect on current understanding of aspects of the behaviour and seismic design of reinforced concrete structures. His many publications are highly regarded internationally for their deep and significant contributions. Indeed many of his publications have become classics. This research work has built on his uncanny ability to appreciate the mechanisms of behaviour of reinforced concrete which has led to a deep understanding of the behaviour of reinforced concrete from the level of elements of members and connections to complete structural systems. He has had the ability to extend this theoretical understanding of reinforced concrete into logical procedures for design, as demonstrated for example by his contributions to capacity design. His work has been characterised by a concern for practical application of theoretical knowledge. His papers have had a decisive influence on the development of building codes, especially in the areas of the earthquake resistance of reinforced concrete structures, both in New Zealand and internationally. His philosophical approach to design has placed him at the forefront of code developments.

His many significant original contributions to the theory of reinforced concrete and to design for earthquake resistance, made either independently or in collaboration with his postgraduate students and his colleagues at the University of Canterbury, have included the mechanisms of the shear resistance of reinforced concrete beams, the transfer of shear across cracks in reinforced concrete by aggregate interlock, the shear and bond transfer mechanisms in beam-column joints, the behaviour of diagonally reinforced coupling beams of structural walls, and the capacity design and detailing for ductility of reinforced concrete moment resisting frames and structural walls. Some highlights of this research work are summarised in the following.

Mechanisms of Shear Resistance of Reinforced Concrete Beams

Pioneering experimental research and deduction by Paulay and Fenwick, first published in 1967(J1) and 1968(J2), brought a new understanding to the mechanisms of shear resistance of reinforced concrete members. For each of the concrete cantilevers between the diagonal tension cracks of the beam in Fig. 1, for beam action the bond force T_1-T_2 between adjacent cracks in Fig. 2 must be resisted by, and be in equilibrium with, the axial force, shear force and moment at the fixed end of the cantilever, the dowel forces at the two cracks and the aggregate interlock at the faces of the two cracks. Their experimental work showed that in beams of normal dimensions and without shear reinforcement not more than 20% of the bond force could be resisted by flexure at the fixed end of the cantilever and not more than 20% by dowel action. Aggregate interlock, arising when the two faces of a crack are given a shear displacement relative to each other, was found to resist about 60% of the bond force. Thus the importance of the shear force resisted by aggregate interlock, ignored as a shear resisting mechanism in members until that time, was identified. It is now commonly accepted that the shear "carried by concrete" in reinforced concrete members comprises shear carried by the compression zone, shear carried by dowel action and shear carried by aggregate interlock, of which aggregate interlock resists the greatest share.

Shear Transfer Across Cracks

The shear which could be transferred across cracks by aggregate interlock was further investigated experimentally by Paulay and Loeber and published in 1974(J11). They determined that the shear displacement required to transfer a given shear stress across two rough interlocking faces in the plane of the shear increases with increase in crack width. Typical shear stress-shear displacement relations were measured by Paulay and Loeber for various crack widths.

Shear and Bond Transfer Mechanisms of Beam-Column Joints

The effects of shear and bond in beam-column joints of moment resisting frames subjected to seismic forces were largely ignored by designers up to the late 1960s. Pioneering research work on the shear strength of beam-column joints after diagonal tension cracking of the joint core due to joint shears, and on the bond performance of longitudinal beam and column bars in joint cores, was conducted by Paulay and Park, first published in 1969(C1), 1973(P4) and 1975(B1). This research work has continued during the last 20 years and has resulted in many further publications. Fig. 3 shows a figure from the 1969 publication (C1), drawn by Paulay, which clearly illustrates the problem of shear (resulting in diagonal tension) and anchorage of bars in exterior beam-column joints. The basic model proposed by Paulay for an interior beam-column joint, published in 1975(B1), is shown in Fig. 4. This model indicates that the forces exerted by the beams and columns at the faces of the joint core are transferred across the joint core by two mechanisms:

(a) A diagonal compression concrete strut [Fig. 4(b)] transferring the concrete compression forces.

(b) A truss mechanism [Fig. 4(d)], consisting of a diagonal compression field of concrete struts and well anchored vertical and horizontal reinforcing bars, transferring the bond forces of the longitudinal beam and column bars.

More recent modifications to the model indicate that some of the bond forces are in fact transferred to the ends of the diagonal compression strut of Fig. 4(b), thus reducing the joint shear required to be transferred by the truss mechanism. Fig. 5 illustrates bond forces near the corners of the joint core being transferred to the strut and the remaining bond forces to the truss.

The design of beam-column joints for shear according to the New Zealand concrete design code* is based on the model shown in Fig. 4. Also, restrictions on the ratio of the longitudinal bar diameter to joint core dimension are imposed to reduce bar slip to an acceptable level. The design of beam-column joint cores is still the subject of international controversy, but during the controversy the Paulay model has remained the main basis of the analytical approach for the calculation of the area of shear reinforcement required in joint cores.

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*"Code of Practice for the Design of Concrete Structures, NZS 3101:1982", Standards Association of New Zealand, Wellington, 1982.

Indeed the model is an early innovative example of the application of strut and tie models to a highly discontinuous or disturbed region of reinforced concrete.

Coupling Beams of Reinforced Concrete Structural Walls

Fascinated by the damage to reinforced concrete coupling beams of the structural walls of the Mount McKinley building in Anchorage, Alaska during the 1964 earthquake (see Fig. 6), Tom Paulay embarked on research into reinforced concrete structural walls which led to his PhD in 1969(T1). His first publication(J4) in the technical literature on walls also appeared in 1969 and has been followed by many very significant contributions since. Paulay's careful experimental study of the behaviour of deep coupling beams, conducted during his PhD research, indicated that conventional longitudinal and transverse reinforcement was inadequate to prevent rapid strength degradation of those beams during cyclic loading which simulated the effects of severe earthquakes (see Fig. 7). This degradation occurs because when the clear span/depth ratio is less than about 1.5 there is a radical redistribution of stresses in the beam due to diagonal tension cracking which results in a spread of tension along the longitudinal top and bottom bars over the whole length of beam leading to significant degradation of strength. With large quantities of conventional (vertical) shear reinforcement, deep coupling beams with aspect ratio of clear span to depth = 1.29 were observed to fail in sliding shear along a vertical section at the face of the wall after cyclic loading, due to a breakdown of the aggregate interlock mechanism. Subsequent studies by Paulay and Binney(J10) revealed that the ductility and useful strength of deep coupling beams can be considerably improved if, instead of using conventional longitudinal and transverse reinforcement, the principle reinforcement is placed diagonally in the beam. Figs. 8 and 9 compare the behaviour of conventionally and diagonally reinforced coupling beams under cyclic loading simulating severe seismic loading well into the inelastic range. For the conventionally reinforced beam (see Fig. 8) no yielding of the vertical reinforcement across the diagonal tension cracks was observed during the cycles of loading. The beam failed by sliding shear without reaching its theoretical flexural strength after limited ductility. The behaviour of the diagonally reinforced beam (see Fig. 9) was excellent, demonstrating extremely ductile behaviour. The model of behaviour of a coupling beam with diagonal reinforcement shown in Fig. 10, proposed by Paulay, leads to extremely simple design equations. The model assumes that after reversed loading into the yield range and diagonal tension cracking in both directions the diagonal bars yield in both tension and compression. A diagonally reinforced beam will only undergo strength degradation if buckling of compression bars occurs. In design it is important to have ties around the bars of a diagonal band to retain the concrete, thus ensuring some lateral rigidity and enabling compression yielding of the diagonal bars to be maintained. Diagonally reinforced coupling beams have now had wide application in New Zealand and other countries. For example, Fig. 11 illustrates the use of such reinforcement in the coupling beams of the structural walls of the New Zealand Parliament buildings in Wellington.

Capacity Design and the Detailing for Ductility of Reinforced Concrete Buildings

Until the late 1960s it was considered in New Zealand that there were too many uncertainties concerning the behaviour of tall reinforced concrete buildings during severe earthquakes to permit their construction. The 1965 New Zealand code for basic design loads required that "All elements of the structure which resist seismic forces or movements and the building as a whole shall be designed with consideration for adequate ductility". No guidelines were given in the code as to how "adequate ductility" was to be achieved. The commentary to the code stated that a safeguard is to limit "the use of reinforced masonry buildings to low structures of minor importance and by building in reinforced concrete in the intermediate field and in structural steel of adequate ductility for taller structures and for those of importance to the community".

Significant research in New Zealand at the universities and elsewhere, and extensive activities of study groups organised by the New Zealand National Society for Earthquake Engineering, in the late 1960s and in the 1970s, resulted in significant strides being made in the development of the capacity design approach and of design provisions for the detailing for ductility to be used in the seismic design of reinforced concrete structures. This activity culminated in the publication of the book on reinforced concrete structures by Park and Paulay in 1975(B1) and in the publication of a greatly improved New Zealand concrete design code NZS 3101 in 1982. As a result, the use of reinforced concrete for the structure of buildings of all heights is now commonplace in New Zealand. The general design provisions of NZS 3101:1982 were based mainly on the 1977 building code of the American Concrete Institute, but many of the seismic provisions had their origins in New Zealand. NZS 3101:1982 has been regarded as a milestone code by many earthquake-prone countries and many of its seismic provisions have been adopted in seismic codes in Europe, South East Asia, North America and South America.

The development of the capacity design procedure specified in NZS 3101:1982 was a significant New Zealand innovation. Capacity design was introduced because of the realisation that the exact characteristics of the earthquake ground motions that may occur at a given site cannot be predicted with certainty and the analytical modelling of some aspects of the behaviour of complete structures is still open to question. Nevertheless it is possible to impart to the structure features that will ensure the most desirable behaviour. In capacity design a mechanism of inelastic deformation is chosen (for example, for moment resisting frames flexural plastic hinges in the beams and columns bases) and the chosen regions of yielding are designed for adequate strength and ductility to resist the design seismic actions. The remainder of the structure is then designed for appropriately amplified actions to ensure that flexural yielding does not occur elsewhere, nor shear failure anywhere, and hence that the chosen mechanism of inelastic deformations will be maintained during the cycles of inelastic deformation imposed by a severe earthquake.

The beginning of capacity design in New Zealand was a logical step by step procedure proposed by Hollings** for achieving adequate ductility in reinforced concrete building structures by ensuring that yielding occurred only in chosen ductile regions. The procedure proposed by Hollings foreshadowed a number of later developments. Paulay has been a leading light in those developments of the capacity design procedures and detailing provisions.

Capacity Design and Detailing of Moment Resisting Frames - Damage to columns of buildings during severe earthquakes has often been irreparable or led to catastrophic collapse. The aim of the capacity design procedure for columns of moment resisting frames is to provide the columns with sufficient flexural and shear strength to ensure that the inelastic deformations of the frame occur mainly by flexural yielding of the beams, rather than by flexural yielding of the columns. That is, soft stories due to sidesway mechansims with plastic hinges only in columns of one storey are avoided. Fig. 12 shows the bending moments in the column of a 12 storey building as obtained from the code equivalent static earthquake design forces compared with the column bending moments induced at various instants during a severe earthquake as obtained by dynamic analysis. The differences between the static and dynamic results are caused mainly by the effects of higher modes of vibration. An innovative contribution by Paulay first published in 1977(J21) was to recommend multipliers whereby the design flexural, axial load and shear actions found in columns due to the equivalent static earthquake design forces could be amplified to take into account the beams reaching their flexural overstrength, the higher modes of vibration of frames and concurrent earthquake loading. The latter two

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**Hollings, J P, "Reinforced Concrete Seismic Design", Bulletin of New Zealand National Society for Earthquake Engineering, Vol. 2, No. 3, 1969, pp 217-250.

effects were derived from the results of non-linear dynamic analysis. The total amplification factor approached two or more (see Fig. 13). The procedure has been widely used in New Zealand and has been much discussed overseas. The logical steps of capacity design and the detailing of reinforcement for adequate ductility of moment resisting frames has been the subject of many papers published by Paulay before NZS 3101:1982 was issued, for example (J15, J19, J21, J22, J23, J24, J26, J28).

Capacity Design and Detailing of Structural Walls - A common conception that was held by many designers is that if walls fail during a severe earthquake it will be by a brittle shear failure. Paulay has shown remarkable insight into wall behaviour and has made a major contribution by demonstrating that, using capacity design, most walls can be designed so as not to fail in a brittle manner. Indeed it was he who insisted that "shear walls" should be referred to as "structural walls", since most structural walls could be designed to deform in a ductile flexure mode if loaded by a severe earthquake into the inelastic range. Paulay was able to illustrate the possible failure modes of structural walls with great clarity. For example, Fig. 14 shows the possible failure modes of cantilever walls. In 1970(T1) and in later publications he also analysed the behaviour of coupled structural walls subjected to seismic loading. He showed that when the strength of the coupling beams is large (that is, $T\ell > M_1 + M_2$ in Fig. 15(b) and (c), noting that the total overturning moment on the wall is resisted by $M_1 + M_2 + T\ell$) the major means of dissipating seismic energy in a well proportioned wall will be by ductile inelastic behaviour of the coupling beams before the walls become inelastic. He also saw the merits of utilising moment redistribution when determining design actions in coupled structural walls (see Fig. 16). In New Zealand ductile coupled walls are now regarded as providing the best means of seismic resistance available for building structures. The stiffness of the walls gives good protection against damage to the non-structural elements and contents of the building. The ductile coupling beams are not part of the gravity load carrying structure and can be easily repaired in the event of damage from an extreme earthquake event. Paulay's research enabled significant strides to be made in formulating the design rules for structural walls in NZS 3101:1982. These rules aim to achieve adequate strength and ductility by ensuring that lateral instability does not occur, buckling of longitudinal compression reinforcement is prevented, the compressed concrete in potential plastic hinge regions is confined, and shear failure is prevented. The capacity design and detailing rules for structural walls, devised single handed by Paulay, were published in many papers by him before NZS 3101:1982 was published, for example (J14, J16, J29, J30, J31), and indeed represent a most noteworthy achievement.

For many years Paulay has conveyed his innovative ideas on