RECENT ADVANCES IN REINFORCEMENT OF DUCTILE CONCRETE MEMBERS AND SHEARWALLS IN TALL EARTHQUAKE RESISTANT BUILDINGS

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As a consulting structural engineer in Southern California since1961, Hanns U. Baumann has been personally involved in the development of over 30 new construction products, mainly related to reinforced concrete construction. An inventor of construction products himself, he has been granted 7 U.S. patents and is co-inventor on 2 additional patents. Beginning in 1960 his Gascon fiber reinforced lightweight polymer concrete system has been used to construct homes in 10 countries. As co-founder of Conspray Construction System, Inc. in 1970, he has pioneered the development of wet shotcrete technology. In 1992 he won the Construction Innovation Forum's Nova Award for his invention of the BaurGrid® Construction System (B/GCS).
BauTech, Inc., founded by Baumann, has been developing and marketing his inventions under exclusive license since 1986. B/GCS was a finalist for the 1996 Civil Engineering Research Foundation (CERF) Charles Pankow Award of the American Society Civil Engineers.
He serves on the Board of Directors of the Construction Innovation Forum, the Civil Engineering Research Foundation, and is Chairman of ACI 439G Reinforcing Steel Committee, Welded Reinforcement Grids Subcommittee, and serves on the Strategic Development Council of ACI International.

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ABSTRACT

Three tall earthquake resistant buildings under construction in California have a new type of reinforcement specified which replaces 1,000 tons of conventional transverse reinforcement. The new reinforcement for ductile concrete shearwalls, and other structural members is called Welded Reinforcement Grid (WRG). One WRG replace many individual hoops and crossties, resulting in saving in labor, materials and construction time.
Testing of WRG at five universities and two national laboratories since 1987 has shown that for both normal strength concrete and high strength concrete elements, ductility is improved when WRG is used as transverse reinforcement.
Results of this testing and new building systems developed with WRG is reported.

1. Introduction

In 1928 Professor F. E. Richart and others at the University of Illinois studied the ductility of unreinforced concrete cylinders loaded axially to failure while subjected to confining fluid pressure. In Figure 1 as shown in Reinforced Concrete Structures [1] by Park and Paulay, page 20, Figure 2.11, axial compressive strength is increased 500% and ultimate strain is increased by 300% when confined by the fluid pressure.

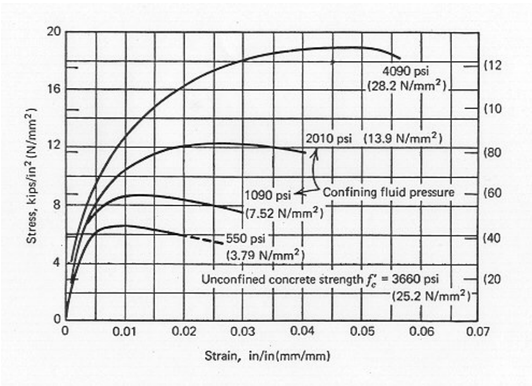

Fig. 1. Axial stress-strain curves from triaxial compression tests on concrete cylinders

This work was carried forward by Professor Bertero and others in the 1960's. Then the research in the 1970's of Professor Newmark and others showed the importance of reliable ductility in the design of earthquake resistant reinforced concrete and steel structures. In the last thirty years, engineers have put much thought and effort into improving the reliability of inelastic deformability of earthquake resistant structures.

2. Conventional Transverse Reinforcement

Until 1987, confinement of the concrete by closely spaced transverse reinforcement using conventional hoops and crossties was recognized by engineers as the only method available to them for their design of ductile earthquake resistant reinforced concrete structures.

3. Problems With Conventional Transverse Reinforcement


Fig. 2. Poor Fitting Hoops

Conventional hoop and crosstie transverse reinforcement has caused many constructability problems to design and construction engineers since the importance of ductility was first recognized. Hoops and crosstie reinforcement is fabricated on benders to very loose dimensional tolerance of ±13 mm (± 1/2"). Poor fitting hoops caused damage to the structure during the Loma Priota earth quake as shown in Figure 2.

Another major cause of the reoccurring constructability problems, is the many layers of closely spaced hoops and crossties which inhibit the flow of concrete during placement. Also the many seismic hooks not only impede the concrete flow but also obstruct the movement of the vibrating compactor.

Another very significant problem of the use of crosstie reinforcement with 90° hooks imbedded in the concrete cover is that during a violent earthquake the concrete cover is lost due to spalling.

[1] R. PARK and T. PAULAY *Reinforced Concrete Structures*, Wiley-Interscience, New York, 1975

Premature crosstie failure in laboratory experiments by Professor Sheik[2] are shown in Figure 3. Based on this evidence, engineers on seismic code writing committees, should be warned and now require seismic hooks at both ends of crossties and should also prohibit 90° hooks in concrete cover.

Fig.3. Crosstie Failure

4. Welded Reinforcement Grids (WRG)

Starting in 1987, a replacement for the constructability problem plagued conventional transverse reinforcement has been under development. Tested in laboratories at five U.S. universities and the national laboratories of Canada and the U.S.. Welded Reinforcement Grids (WRG) have solved constructability problems. Also members reinforced with WRG have shown ductile performance superior to those with conventional transverse reinforcement. Professor Murat Saatcioglu[3] attributes this superior ductile performance to the welds at each intersecting rod of the WRG which creates many smaller confinement cells inside the structural member.


Fig. 4. BauGrids® as Shearwall Reinforcing

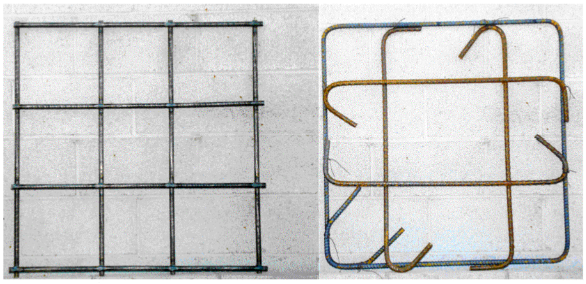
Fig. 5. BauGrids® vs. Conventional Hoops and Crossties

The WRG are manufactured under a very strict quality assurance program approved and monitored by International Council of Building Officials (ICBO) which in 1999 issued an Evaluation Report ER-5192. Similar approvals have been issued by the cities of Los Angeles, San Francisco, San Diego, Phoenix and New York.


Fig. 6. 17-Story Dormitory at SFSU

5. BauGrid® Reinforcement System (B/GRS)

Welded Reinforcement Grids (WRG) is the generic name for proprietary products BauGrid® Reinforcement System (B/GRS) that is commercially available through BauTech, Inc. of San Clemente, California, U.S.A. The BauGrid® Reinforcement System (B/GRS) has been specified in increasingly larger projects since 1988 when it was first used as shearwall confinement reinforcement

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[2] Sheikh, M. and Toklucu, M., 1993, "Reinforced Concrete Confined by Cylinder Spirals and Hoops", *ACI Structural Journal, September-October*

[3] Saatcioglu, M. and Grira, M., 1996, "Concrete Columns Confined with Welded Reinforcement Grids," *Ottawa Carleton Earthquake Engineering Research center - Report OCEERC 96-05, September.*

in a 17-story San Francisco State University dormitory after being tested at the University of California, Irvine by Professor Shepherd, and at University of California, Berkeley by Professor Bertero[4]. The excellent performance of the structure during the 1989 Loma Prieta earthquake justified the use of higher ductility factors in the earthquake design, which significantly reduced labor, material and time to construct the 17-story dormitory which has 18 cm (7") thick bearing/shearwalls. An earlier preliminary design with conventional reinforcement and, consequently lower ductility factor design, required 25 cm (10") thick walls.

6. BauCages® with BauSplicegrids™

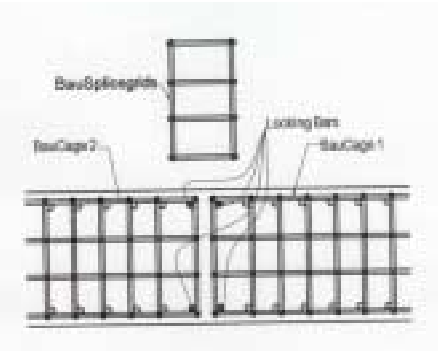

Fig. 7. BauSplicegrids™

Fig. 8. BauCages® Installed with BauSplicegrids™

A 24-story building constructed in San Diego California, U.S.A utilized a proprietary product developed by BauTech to speed construction of heavily reinforced concrete bearing /shearwalls around the elevator core. Two-story high by up to 3.7 m (8') wide BauCages are installed and then quickly connected on their common vertical edges by first insertion of BauSplicegrids™ and then charging vertical locking bars. The contractor reported a 50% labor reduction in cage assembly and 40% labor reduction in cage installation.

7. Large BauCages®

Fig. 9. T Shaped BauCages®

A 42-story building in San Francisco has over 500 tons of 2.4mx2.4m(8'x8') L-shaped, T-shaped BauGrids® specified in 61 cm (24") thick concrete elevator core boundary shearwalls. The contractor, Webcor, reports labor saving in assembly and installation similar to those reported by the contractor in San Diego. The BauGrids® with 16mm (5/8") diameter welded rods are shipped very efficiently on pallets to the BauCage® assembly plant. There BauCages® are rapidly assembled with very few workers, because often one BauGrid® replaces up to 32 separate pieces of conventional reinforcement.

[4] Bertero, V., Miranda, E. and Thompson, C., 1990, "Cyclic Behavior of Shear Wall Boundary Elements Incorporating Prefabricated Welded Wire Hoops, *Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, January.*

8. BauLinkbeam™

The BauLinkbeam™ is a new proprietary BauTech product for use as coupling beams in ductile shearwalls. Because BauGrids® are manufactured to very exact dimensional tolerance ±3mm(±1/8"), BauCages® with BauLinkbeam™ can be fabricated so that when BauCages® are quickly assembled on-site, the whole element has a dimensional accuracy of ±6mm (±1/4"). The BauLinkbeams™ horizontal and diagonal bars can then be rapidly charged without hitting the vertical boundary element bars.

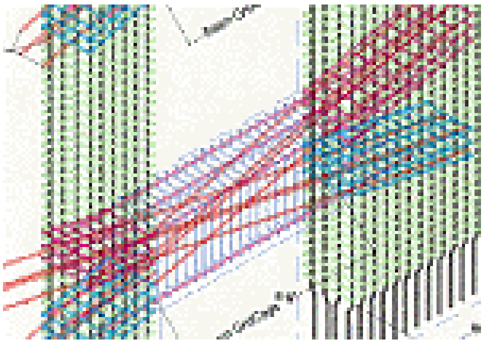

Fig.10. BauLinkbeam™

9. BauLapsplice™

When BauGrid® are specified to confine rebar lap splices, the lap splice length is shorter which saves a significant amount of material. Tests have been done on specimens where the forms were placed directly against the specimen BauCages®. This simulated a completely spalled condition. Because the welds fully develop the rod strength, the "spalling" of concrete cover is of no concern when using BauLapsplices™.

10. BauCorbels™

BauCorbels™ are either preassembled at the plant or shipped as kits to the site where the workers can quickly assemble the BauCorbel™ without any field welding.

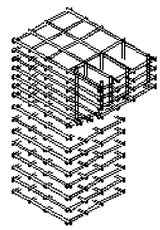

Fig. 11. BauCorbel™

11. Crossing BauLadders™

Because of their exact manufacturing tolerances, BauLadders™ can be made of two exact heights so that they can be positioned orthogonally. This unique property allows the shipping of Crossing BauLadder® kits to the site in very compact packages. At the site, the taller BauLadders® are set into a simple portable fixture and then the shorter BauLadders® are changed at 90° to the taller BauLadders® to make a BauLadderCage™ assembly.

12. BauShearhead/Frame™

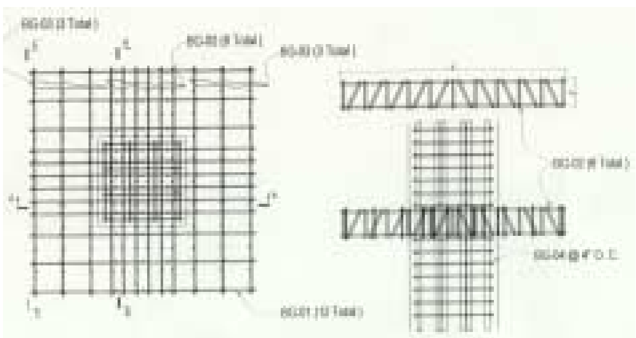

Fig. 12. BauShearhead/Frame™

Using Crossing BauLadders®, an efficient shearhead can be created very rapidly. Column-slab joints with BauShearhead/Frame™ reinforcement in the slab and BauCage® reinforcement in the column can be designed as frame joints to resist lateral wind and gravity loads in both low and high rise structures.

13. BauFooting™/BauPilecap™

Similarly BauLadderCage™ kits can be sent to the site where they can be quickly assembled. Lower strength concrete can be specified and in some cases soil cements can be specified to construct very economical structural members.

14. BauRetainingwall™

BauRetainingwall™ kits with BauLadderCages™ for both short and very tall retaining walls can be compactly shipped to the site where they can be quickly assembled. For shorter walls, soil cement, made on-site, can be used to construct a very economical retaining wall system. For taller retaining walls the BauRetainingwall™ kits include corrosion protected BauLadders® that can be installed as tiebacks as the soil is placed and compacted behind the BauRetainingwall™.

15. BauPlanterwall™

The BauPlanterwall™ has been developed to meet the specifications of the California Department of Transportation (Caltrans). The face of the wall slopes at an angle of 1:6 (1 horizontal to 6 vertical) and is left open so that planting material can be installed. For lower height retaining walls a soil cement can be used instead of concrete. The BauPlanterwall™ kits are either sent to the precast yard or sent directly to the job site where the concrete or soil cement is placed into the BauCage®.

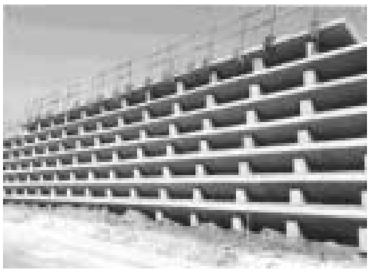

Fig. 13. BauPlanterwall™

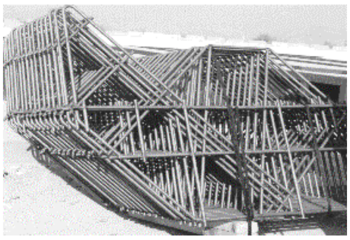

Fig. 14.
BauGrid® in BauPlanterwall™

16. BauPreformed BauCages®

The exact dimensions of BauGrids® permits the simple attachment of reusable or stay-in-place BauForms™ to the outside of the BauCages®. The stay-in–place BauForm™ is made of a low cost wire fabric or other materials. For certain applications such as for BauFences™ and BauGardenwalls™ a planting material is placed inside and the stay-in-place BauPlanterfabric™ both holds the planting material and allows the growth to come through the openings. Automated equipment can be used at the plant to attach the BauForm™ to the BauCage®, or it can be quickly attached to the BauCage® at the job site. Preformed BauCages® with BauFabricform™ can provide an inexpensive method for rapid construction of civil structures where the quilted surface of the concrete members is not objectionable. Expandable BauCages® with BauFabricform™ preattached can offer a rapid and low cost method of constructing of pumped-in-place reinforced concrete civil structure such as pipes, culverts, retaining walls, bridges where a quilted surface is acceptable.

17. BauCladding™

BauCladding™ is a material that is applied in the plant and clads the outside of the BauCage®. BauCladding™ has special properties of very low permeability and superior fire resistance. The BauCage® with BauCladding™ is designed so that the light BauPreclad™ members are shipped from the plant and easily installed using a small crane. The BauCladding™ has sufficient strength to resist the outward pressures as the preformed BauCages® are quickly filled with self compacting concrete, rapid bottom-up-pumping through a valve at the base of the wall or column will be possible. Only simple rebar lap splice connections are needed.

18. BauTree™

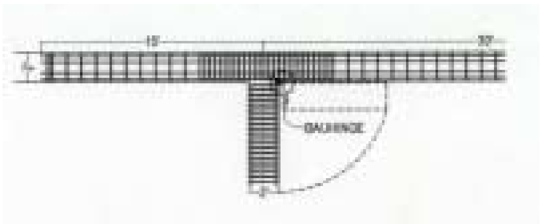

Fig. 15. BauTree™

Frames of column-beam cages can be rapidly assembled to make BauTrees™. Single-story or two-story BauTrees™ can be quickly set in place as one piece. A BauHinge™ attached at the top of the column BauCages® to the beam BauCage® will allow the BauTrees™ to be shipped from the plant as one piece without column rebar. At the site the column BauCages® will be rotated into position and then the column rebar charged. The BauTree™ can be shipped with a bare BauCage® or with PreFormed™ or PreClad™ BauCages®.

19. The PRESSS Hybrid System

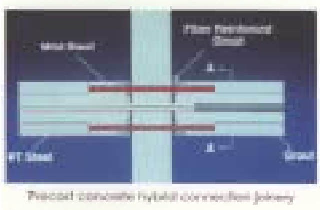

Fig. 16. PRESSS Test at NIST

Starting in 1993 BauTech, Inc. has been a development team member on the PRESSS Hybrid System Development Project. The PRESSS Program has been sponsored mainly by Mr. Charles Pankow and his Charles Pankow Company, and also partially funded by National Science Foundation (NSF) and Precast/Prestressed Institute (PCI).

The goal of the PRESSS program was to develop a precast concrete construction system that could be used to economically construct tall buildings in regions of high seismicity. From 1993 to the present, BauTech, Inc. has supplied BauGrids® first for extensive testing at the National Institute of Science and Technology (NIST), University of Washington, University of California, San Diego, and then for projects of ever increasing size in California and New York. The BauGrid® Reinforcement System was instrumental in the successful design and construction of the world's tallest precast concrete building at 3rd & Mission in San Francisco in a region of highest seismicity.

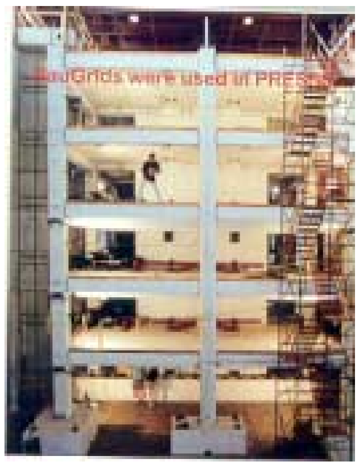

Fig. 17. PRESSS Test at UCSD

The Hybrid structural system is composed of frame joints with both mild reinforcement and prestressed reinforcement. The design and construction team put a great deal of thought and effort into not only making the precast structure earthquake resistant but making it constructable. The BauGrid® Reinforcement System proved to be the answer to the need to hold very exact dimensional tolerances so that the precast elements could be fit together rapidly and the prestress strand and mild reinforcement easily installed.

Test of a 60% scale five-story structure at UCSD by Professor Priestly and Professor Sieble showed that this hybrid structure will very likely require much less post-earthquake repair than conventional poured-in-place structures.

The beautiful 39-story structure, designed by Robert Englekirk Consulting Engineers, CA, has curving spandrel beams that efficiently resist both gravity and lateral forces while also serving as handsome exterior walls.

Fig. 18. 3rd & Mission, SF

Fig. 19. BauGrids® for Moment Frame Columns

Fig. 20. BauGrids® on 8' Flatbed Truck

20. BauCMU™ System

BauTech, Inc. is developing the BauCMU™ System for construction of tall earthquake resistant buildings constructed with special Concrete Masonry Units (CMU) and a special mortar. Tall building constructed with frames and shearwalls using the BauCMU™ System will very likely have post earthquake repair costs less than buildings constructed with conventional cast-in-place concrete structural systems. Ductile inelastic deformability of the BauCMU™ System without significant damage, is based upon a design of the frames and shearwalls using a BauBlock™ which is a standard double open end block modified to accept horizontal BauLadders® at 10 cm (4") on center. The special BauFlexmortar™ is designed to allow the BauBlock™ to articulate as the BauLadders® in the high strength grout resist most of the gravity and lateral forces applied to the frame and shearwalls.

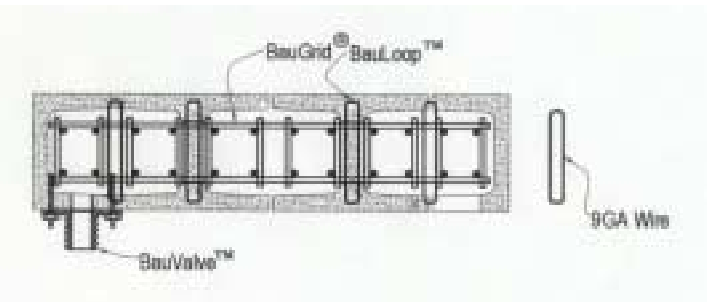

Fig. 21. BauCMU™