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Cyclic shear tests of gypsum roof diaphragms

Mehrdad Mehrain & William E. Gates
Dames & Moore, Los Angeles, Calif., USA

ABSTRACT: The Uniform Building Code allowable shear values for gypsum diaphragms are based on static load tests using monotonically increasing load. Considering the expected relative brittle behavior of gypsum roofs, it is important to determine the performance of this type of construction under reverse loading conditions that are expected to occur during severe seismic motions. Several 1.83m square panels of gypsum roof with different steel subpurlins and reinforcing steel mesh were cut out of actual building roofs and were tested in the laboratory under static cyclic racking shear loads at various drift levels to determine the loss of stiffness and strength due to cracking and large displacements. Observed levels of inelastic deformation and associated damage to the diaphragm specimens were used to define acceptable performance levels for life safety and damage control.

1 INTRODUCTION

Gypsum roofs were widely used in the 1950's and 1960's, due to their advantages of light weight, economy, fire protection and thermal insulating properties. The seismic design of these gypsum roof diaphragms was based on the requirements of the Uniform Building Code (ICBO, 1991) which has remained essentially the same to this date. The code requirements are based on a series of static tests performed in the 1950's and early '60's on this type of roof system. In these tests, monotonically increasing in-plane loads were applied to the diaphragm beam specimens to failure.

The use of gypsum roof structures has been significantly reduced since 1970's. Gypsum manufacturers lost interest in the use of this product as a roof system and subsequent testing and research on this product was stopped. Thus, building code requirements for gypsum roof diaphragms are still based on the original tests performed some 30 years ago. The primary factors that demonstrated the need for this test program were as follows:

1. Brittle performance of gypsum is not directly accounted for in the existing code allowable shear values.
2. Earthquake damage to gypsum roofs has been observed in moderate earthquakes.
3. Information on strength and stiffness degradation is lacking.
4. Data on relationships between deformation and damage state is needed in seismic upgrade design.

The results of these tests are to be used in a nonlinear stiffness degrading non-linear dynamic analysis to establish design criteria for various levels of desired diaphragm performance.

1.1 Structural System

The structural system of gypsum roof diaphragms consists of a 5 to 7.5 cm thick gypsum that is poured over form boards which are supported on the lower flange of steel subpurlins. The subpurlins are spaced typically at 81 cm on center and are supported by steel beams and girders. Figure 1 indicates the general configuration of the typical gypsum roof construction.

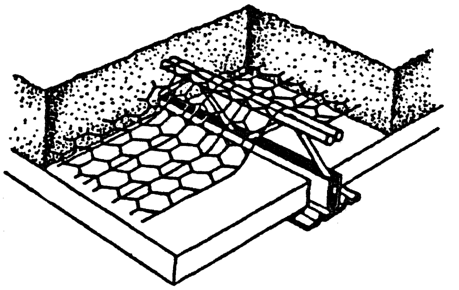

Figure 1. Configuration of gypsum roof with truss-T

Two basic types of subpurlins are used:

- Truss-T, in which the subpurlin consists of cold rolled wire top flange and web members and sheet steel angles acting as lower flange and as support for form boards.
- Bulb-T, in which the subpurlin is a rolled structural steel section.

Gypsum roofs are reinforced with steel mesh that may be one of the following:

- 6x6 - 10x10 wire mesh
- 4x8 - 12x14 wire mesh
- Keydeck mesh consisting of woven mesh with additional transverse reinforcement.

In gypsum roof diaphragms, the shear resistance is solely provided by the reinforced gypsum. Other critical force resisting elements of the diaphragm, such as drag struts and chords, are provided by other structural members.

1.2 Previous Investigations on Gypsum Roof Diaphragms

Previous tests of gypsum roof diaphragms are limited to the gypsum industry sponsored studies performed in the 1950's and early 1960's. (S.B. Barnes & Associates, 1955, 1956, 1958, 1962).

These tests used monotonically increasing loads and provided the experimental basis for the Uniform Building Code allowable shear values by dividing the ultimate shear capacity obtained from tests by a factor of safety of 3.0.

2 CYCLIC LOAD TEST PROGRAM

The original static diaphragm tests performed in the 1950's and '60's used test specimens loaded as simply supported beams with concentrated in-plane loads at the midspan or at the third points. The size of the samples was typically 2.44m by 4.88m. Some larger samples of 4.88m by 9.76m were also tested to determine the effect of specimen size. It was found that sample size, in the range considered, did not have a significant effect on the test results.

In the test program reported in this paper, the specimen size was nominally 1.83m by 1.83m representing a typical interior portion of roof with two subpurlins. The specimens were cut from actual buildings and transported to the laboratory using a special wood pallet system with soft cushions designed to ensure that the specimens would not be damaged during cutting and transportation.

2.1 Test Set Up

The test specimens were loaded as cantilever diaphragms as shown in Figure 2. This approach is typically referred to as a "racking" test. The test frame consisted of a steel frame using wide flange shapes with a diagonal bracing element for added rigidity. A double-acting hydraulic jack was used for application of cyclic load. Attachment angles were used for transfer of load to the gypsum. These angles were connected at each specimen corner with a single bolt to form a hinged frame. Effectively, no resistance was provided by the attachment angles against distortion into a parallelogram shape as the specimens were subjected to shear loads. Steel rollers were provided to prevent out of plane motion along the loaded edge of the specimens.

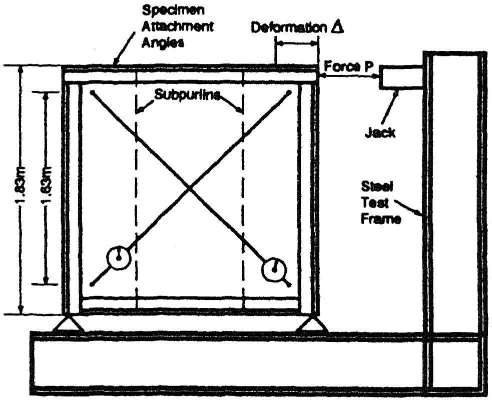

Figure 2. Test Setup

The specimen deformation was obtained by reading two dial gauges placed on the gypsum material and measuring the change of length along the two diagonals. The readings of the hydraulic jack and dial gauges were fed into a personal computer where this data was stored and analyzed to automatically plot the force-deformation relationship as the test progressed.

All specimens had Class A gypsum. Other properties of the specimens were as follows:

Specimen No.	Subpurlin	Reinforcing Mesh
1	Truss T	4x8 - 12x14
2	Truss T	6x6 - 10x10
3	Bulb T	4x8 - 12x14

2.2 Connection Tests

Several preliminary small scale tests were performed to evaluate the different procedure for load transfer to the gypsum specimens. This consisted of using bolts, plugs, cement injection and prestressing to transfer load by friction. These tests were performed on newly poured gypsum blocks as well as on small specimens cut from the buildings.

The final approach selected and successfully used for load transfer consisted of two 10.2 x 7.6 x 0.64 cm attachment angles that were in contact with gypsum through a layer of poured cement. The angles were tightly pressed against the top and bottom of the specimens to a compressive stress of approximately 7 kg/cm^2 by tightening the connecting bolts. The bolts were placed in oversized holes in order to prevent direct bearing between bolt and gypsum. Preliminary tests showed that bolts bearing against the gypsum caused premature splitting failure of gypsum due to the small edge distance.

2.3 Gypsum Strength Tests

Compressive strength tests were performed on 5 cm cube samples obtained from the buildings in the vicinity of main shear test specimens. These tests indicated that all specimens met the minimum specified strength for Class A gypsum.

2.4 Cyclic Diaphragm Load Tests

For the cyclic load tests, the basic loading sequence consisted of two complete cycles of displacements at 0.13, 0.25, 0.38, 0.51, 0.76 and 1.0 cm followed by one complete cycle at successively higher displacements until failure. Furthermore, some cycles were followed by a complete loading cycle at 1/2 to 2/3 the previous maximum displacement. The loading included additional cycles depending on the observed damage to obtain additional information at various stages of the loading in order to better represent the simulation of the actual behavior for use in the subsequent analysis phase of this study.

At various levels of displacement, the size of cracks in terms of horizontal gaps and vertical out-of-plane offsets were measured and recorded. Furthermore, the degree of damage to and repairability of the specimens associated with each stage of loading was judgmentally decided.

At various loading stages the specimens were subjected to additional vertical "live" load by standing on the gypsum deck. The added load was on the order of 150 to 200 kg/m^2. All specimens were found to be capable of carrying the added gravity load when subjected to deformations well in excess of the acceptable levels of damage.

3 TEST RESULTS

Figures 3, 4, and 5 show the force displacement curves obtained from the tests of the three gypsum roof specimens. The curves show the portion of test data associated with displacements in the range of acceptable damage to be used later in the nonlinear dynamic analysis.

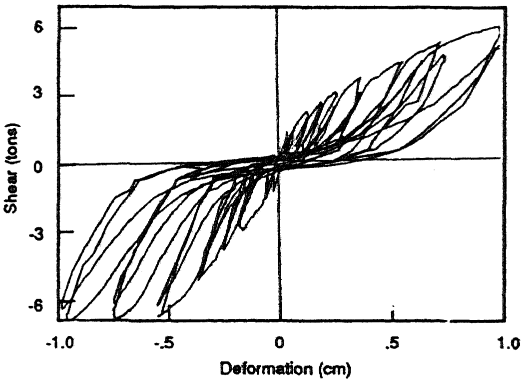

Figure 3. Specimen no. 1 force - deformation relationship

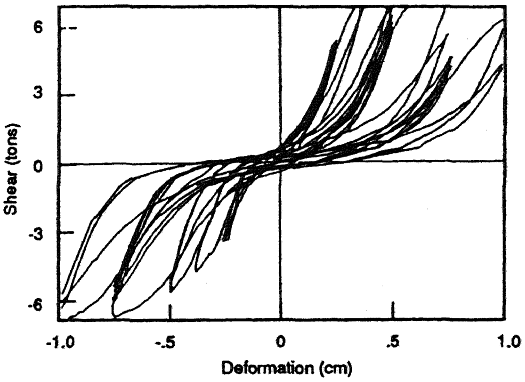

Figure 4. Specimen no. 2 force - deformation relationship

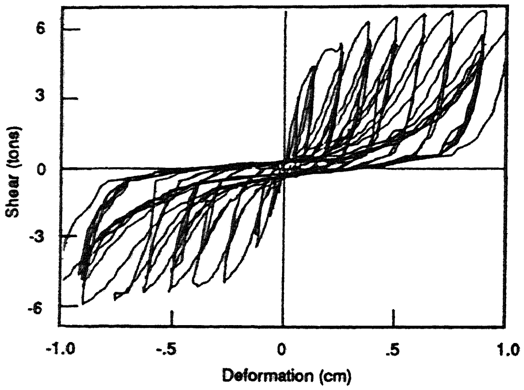

Figure 5. Specimen no. 3 force - deformation relationship

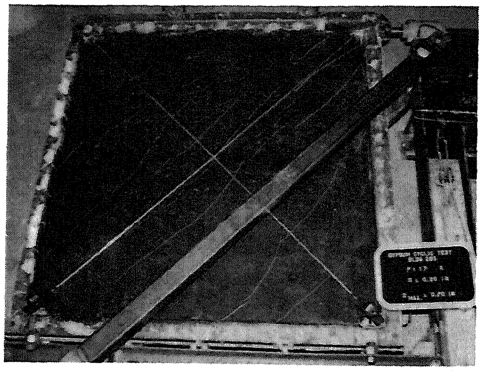

Figure 6. - Truss-T specimen at 0.5 cm drift

These curves show very high stiffness degradation due to cracking. However, as the deformation of the previous cycle of loading is exceeded, the specimens picked up resistance almost to the level of the previous cycle. It can therefore be concluded that the deterioration of strength is not as severe as degradation of stiffness. The testing program provided the following additional observations:

Crack Pattern. The specimens with truss-T subpurlins had well distributed cracks inclined at approximately 45 degrees to the direction of applied load (Figure 6). Major part of the deformation appeared to be related to the opening of these cracks.

In the specimen with bulb-T subpurlins, major cracks were parallel to and located directly above the bulb-T's (Figure 7). The post-cracking deformation of this specimen was primarily due to sliding along these cracks. This deformation pattern is not kinematically consistent with the attachment angles which were rigidly connected to the specimen. It is suspected that additional resistance against displacement was provided by the frame formed by the attachment angles. However, due to the observed severe stiffness degradation of this specimen (similar to that of the truss-T specimens), it appears that the effect of boundary conditions on strength and stiffness was not substantial.

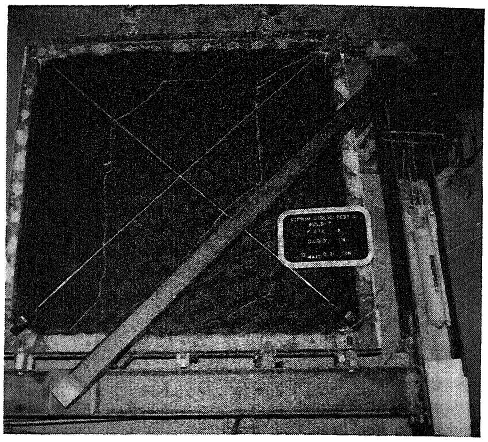

Figure 7. - Bulb-T specimen at 0.75 cm drift

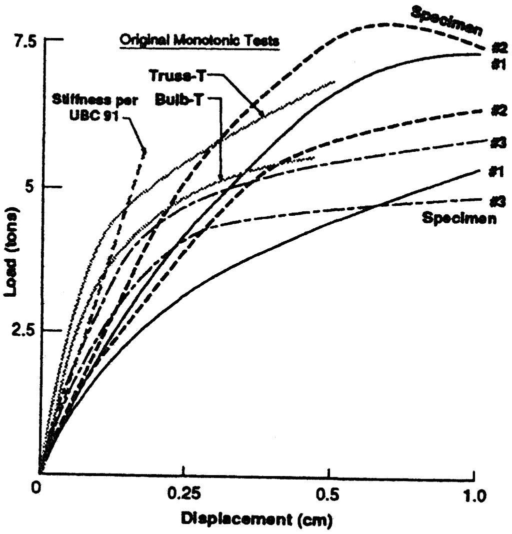

Figure 8. Force Displacement Envelope

The observed crack pattern in the specimens for both types of subpurlins is generally consistent with the crack pattern of the original monotonic tests performed in the 1950's and '60's.

Shear Strength. Figure 8 shows the envelope of the force displacement relationships presented in Figures 3 through 5. Each specimen has two envelopes, one for the positive and another for the negative directions of loading. Since the average thickness of the gypsum was not the same in all 3 specimens (5.1 cm in specimen #1, 5.7 cm in specimen #2 and 6.4 cm in specimen #3), the force values of specimens #2 and #3 were adjusted to obtain comparable strength of all 3 specimens. Figure 8 also shows the typical results of the original monotonic load tests (also adjusted for thickness).

The following observations can be made regarding comparison of the various tests:

a. The maximum strengths obtained from the cyclic tests and the original monotonic tests appear to be consistent.

b. Specimen #1 exhibited smaller initial stiffness due to the initial cracked condition in which the specimen was delivered to the laboratory. Specimen #3 was virtually uncracked, and its initial stiffness is in better agreement with the results obtained from monotonic tests.

c. The strength for the bulb-T sample did not appear to be much lower than the truss-T specimens. However, this could be related to the nature of initial cracks and the effect that the forced boundary condition could have in increasing the apparent shear resistance of the specimen. Again, the severe stiffness degradation seems to imply that the effect of boundary condition was not significant in strength and stiffness.

The shear deformation corresponding to maximum permissible damage was judgmentally selected during the tests to be 1.0cm. The max deformation for minor damage was selected to be 0.5 cm. These values correspond to shear strains of .0062 and .0031, respectively.

4 CONCLUSIONS

Gypsum diaphragm test data of this study indicates that this material exhibits substantial degradation of stiffness when subjected to severe cyclic loads. The force-deformation relationship obtained from these tests can be used in a stiffness degrading non-linear dynamic analysis program to provide realistic seismic design criteria for the desired performance level based on actual cyclic behavior of gypsum roof systems.

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