Appendix A
SUPPORTING DOCUMENTS FOR CHAPTER 2

This appendix contains the supporting documents that are referenced in Chapter 2 of this report. All of the documents contained in this appendix are reproduced with permission of The Port Authority of New York and New Jersey. Table A–1 contains a summary of supporting documents and their location within this appendix. The footnote numbers given in the table correspond to those in Chapter 2.

Table A–1. Supporting documents for Chapter 2.

Footnote Number	Document Title	Page(s)
Section 2.1 – Building Codes Used In Design		
1	Letter dated May 15, 1963 from Malcolm P. Levy (Chief, Planning Division, World Trade Department) to Minoru Yamasaki (Minoru Yamasaki & Associates)	132
2	Letter dated February 18, 1975 from Joseph H. Solomon (Emery Roth & Sons) to Malcolm P. Levy (Chief, Planning Division, World Trade Department)	133
3	Letter dated September 29, 1965 from Malcolm P. Levy (Chief, Planning Division, World Trade Department) to Minoru Yamasaki (Minoru Yamasaki & Associates)	136

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A. Schreier

RECEIVED

THE PORT OF NEW YORK AUTHORITY

111 Eighth Avenue at 15th Street New York 11 N.Y.

ALGONQUIN 5-1000

WORLD TRADE CENTER

Malcolm P. Levy
CHIEF, PLANNING DIVISION

Richard C. Sullivan
DIRECTOR

May 15, 1963

Mr. Minoru Yamasaki
Minoru Yamasaki & Associates
1025 East Maple Road
Birmingham, Michigan

Dear Yama:

At a recent meeting with Mr. John Kyle, Chief Engineer, the subject of New York City Code compliance was further amended as follows:

"All consulting engineers and architects working on the World Trade Center have been instructed to comply with the Code in preparing their designs. Questions have arisen, however, in areas where the Code is not explicit. It was agreed that in such cases and, where technological advances make portions of the Code obsolete, the consultants may propose designs based on acceptable engineering practice. All such instances will be called to the attention of The World Trade Center Planning Division. When preliminary designs have been completed, the Chief Engineer will review all design concepts with the appropriate municipal agencies before the consultants proceed with the final design".

Sincerely,

Malcolm P. Levy
Chief, Planning Division

LF:db
cc: Mr. J. Roth (ERS)

(2.1)

EMERY ROTH & SONS
850 THIRD AVENUE, NEW YORK, N. Y. 10022 (212) 753-1733

RICHARD ROTH, SR., F. A. I. A.
HARRY J. HARMAN, A. I. A.
RICHARD ROTH, JR., A. I. A., R. I. B. A.
JOSEPH H. SOLOMON, A. I. A.

JULIAN ROTH
ADMINISTRATION
ESTELLE BEAL
CONTROLLER
PHILIP MARTINES
CHIEF DRAFTSMAN

February 18, 1975

Mr. Malcolm P. Levy
General Manager
World Trade Center Operations
Port Authority New York, New Jersey
1 World Trade Center
New York, New York 10047

RE: WORLD TRADE CENTER

Dear Mal:

In accordance with the instructions issued by the Port Authority at the start of the project, construction drawings for the World Trade Center were to conform with requirements of the Building Code of New York City, and any variations therefrom were to be called to the attention of the Port Authority for final decision and authorization. This procedure has been followed in production of the contract drawings and, with the exceptions authorized by the Port Authority noted below, the drawings are in accordance with the new Building Code adopted in December, 1968. The Building Department reviewed the tower drawings in 1968 and made six comments concerning the plans in relation to the old code. Specific answers noting how the drawings conformed to the new code with regard to these points were submitted to the Port Authority on March 21, 1968.

We were instructed by the Port Authority to deviate from code with respect to the following areas:

1. Omission of vents from closed shafts. Noted to the Port Authority by letter dated April 20, 1967.

2. Demising partitions to stop at suspended ceiling or bottom of truss instead of running from slab to slab. Noted to the Port Authority by letters dated November 9, 1967 and June 6, 1969 with response on December 12, 1967. Prior instruction on procedure from Port Authority dated January 26, 1966.

3. Omission of fire protected openings on exterior walls with separation of less than 30 feet. Noted to Port Authority by copy of letter to MYA dated January 26, 1966.

4. Treatment of concourse level as "Underground Street" noted by letter to the Port Authority on April 6, 1971, January 11, 1972 and May 7, 1973.

Fire detection and protection requirements specified for the World Trade Center meet or exceed Building Code requirements prior to the adoption of Local Law #5. Most other office towers in the City of New York meet the minimum code requirements:

A. Telephone system for Fire Department use connecting pump room and gravity tank room with all floors. A six inch gong provided at permanent telephone at pump room, first floor and gravity tank room. Telephone jacks at all other floors protected by break glass boxes.

B. Standpipe signalling device: an eight inch gong located in the pump room and every 10 floors in the elevator shaft; an approved closed circuit strap key enclosed in a sheet metal box at each telephone station for fire department use.

The Building Code permits the use of louvered doors on toilet rooms, janitor and electric closets located in 1 hour rated corridors. There is no size limit specified for the louver, but the Board of Standards and Appeals permits louvers of 2 square feet in 3/4 hour rated doors (which are required in 1 hour rated partitions). Up until about 1968 most office buildings had 1 hour minimum rated enclosures and louvered doors in telephone closets and sleeves or small slots through the floor. Since 1968, about 25 percent still have louvers in the doors. In more recent buildings the floor openings have been slabbed over.

Since corridor construction is required by code to be 1 hour rated, it follows that louvered doors were acceptable in tele-

EMERY ROTH & SONS -3- February 1[illegible] 1975

phone closets. Corridor partitions in the Trade Center Towers, however, were designed to meet 2 hour rated construction at the request of the Port Authority, to forestall any problems with dead end limitations in the new code. It would require investigation of individual floor tenant layouts to determine if the dead end limitation of 50 feet for 1 hour construction has been exceeded.

The original contract drawings, dated 7/31/67 and the Contract Bid Sets dated 12/18/67 and 2/9/68 indicate 2 hour rated enclosures for the telephone closets with louvers in a FPSC, 1-1/2 hour label door. The hollow metal door specification written in 1967 and received by the Port Authority on 10/24/67 called for fusible link dampers on louvers in labeled doors. Letters to the Port Authority dated 8/23/67 and 9/6/67 incated that variances had been obtained for omission of dampers and requested instruction regarding this advice. The requirement for dampers was deleted from the final draft of the specification reviewed by the P.A. in May, 1968. Re quirement to meet provisions of underwriter's labs, B.S.A. and Building Department was retained, however, for doors with F.P.S.C. and hourly ratings.

Based on Port Authority comments on drawings received 4/17/69 and pursuant to a letter from the Port Authority to Tishman Construction Company dated 4/28/69 instructing that such changes be made, the wall of the telephone closet was changed to 1 hour rated construction on 5/23/69 and the door was changed to F.P. with a 1-1/2 hour rating. Since the telephone closet was no longer a shaft with a 2 hour rated enclosure, all floor openings left for future installation of cables had to be firestopped. This admonition was reiterated in a letter to the Port Authority dated June 25, 1973.

Please inform us if any additional information is desired.

Sincerely,

EMERY ROTH & SONS

Joseph H. Solomon

JOSEPH H. SOLOMON

JHS:am

CC: Mr.R. Monti, Chief Engineer/ PA

6211
R 110-4

THE PORT OF NEW YORK AUTHORITY

111 Eighth Avenue at 15th Street New York NY 10011

620-8233

WORLD TRADE CENTER

Malcolm P. Levy
CHIEF, PLANNING DIVISION

Richard C. Sullivan
DIRECTOR

cc R.40-1

September 29, 1965

Mr. Minoru Yamasaki
Minoru Yamasaki & Associates
1025 East Maple Road
Birmingham, Michigan 48011

Dear Yama:

We have decided to adopt the new Building Code presently existing in second and third draft form for The World Trade Center.

The Roth office is requested to revise floor plans as quickly as possible and on an accelerated basis to comply with the provisions of this code. It is my understanding that the present drawings have been prepared to permit rapid conversion to the new code. Generally the tower core should be redesigned to eliminate the fire towers and to take advantage of the more lenient provisions regarding exit stairs. No other major change to the core should be undertaken without review by this office.

The structural consultants are instructed, by copy of this letter, to revise structural design in accordance with the more realistic criteria for partition weight allowance. The majority of interior partitions, as noted in a previous letter, will consist of reinforced gypsum plank.

The Roth office is requested to provide me with the dates on which we can expect revised floor plans and also to indicate any changes in design schedule caused by these instructions.

Sincerely,

Malcolm P. Levy

cc: R. Baum (JBB), J. Loring (JRLA), J. Roth (ERS), J. Skilling and L. Robertson (WSHJ)

Similar letter sent to Mr. Julian Roth (ERS)

Appendix B
SUPPORTING DOCUMENTS FOR CHAPTER 3

This appendix contains the supporting documents that are referenced in Chapter 3 of this report. All of the documents (with the exception of the Laclede Steel Company correspondence) contained in this appendix are reproduced with permission of The Port Authority of New York and New Jersey. Table B–1 contains a summary of supporting documents and their location within this appendix. The footnote numbers given in the table correspond to those in Chapter 3.

Table B–1. Supporting documents for Chapter 3.

Footnote Number	Document Title	Page(s)
	Section 3.3 – Damping Unit Tests	
2	Letter dated June 22, 1967 and enclosure from Don Caldwell of 3M to Peter Chen of SHCR (WTCI-501-L; reproduced without appendices that are contained in WTCI-501-L)	139
3	"Test Program for World Trade Center Viscoelastic Damping Units," by Stephen H. Crandall of MIT, May 20, 1968 (WTCI-501-L)	146
4	"Test of Viscoelastic Damping Units for World Trade Center Tower Buildings," S.H. Crandall and L.E. Wittig, April 23, 1969 (Box 9, 233 Park Ave.)	158
5	Letter dated August 29, 1968 from Leslie E. Robertson of SHCR to Malcolm P. Levy of PONYA (WTCI-501-L)	179
6	Letter dated May 22, 1969 from Leslie E. Robertson of SHCR to Malcolm P. Levy of PONYA (WTCI-501-L)	182
7	Letter dated June 2, 1969 from Stephan H. Crandall of MIT to John M. Kyle of PONYA (WTCI-501-L)	185
8	"World Trade Center Report No. DU-3, Viscoelastic Damping Units," by SHCR, June 2, 1969 (WTCI-501-L; reproduced without appendices that are contained in WTCI-501-L)	189
9	Letter dated November 5, 1971 from Malcolm P. Levy of PONYA to Don Caldwell of 3M (WTCI-513-L)	196
	Section 3.4 – Floor Truss Tests	
10	Letter dated April 3, 1969 from David B. Neptune of the Laclede Steel Company to W.C. Borland of PONYA (WTCI-503-L)	197
11	Internal Laclede Steel Company memo dated May 15, 1969 from David B. Neptune to R.D. Bay (part of WTCI-82-I)	198
12	Internal Laclede Steel Company memo dated September 7, 1967 from J.R. Paul to A.C. Weber (WTCI-85-I)	202
13	Letter dated August 10, 1967 from A. Carl Weber of the Laclede Steel Company to Wayne Brewer of SHCR (WTCI-235-L)	203
14	Letter dated April 19, 1968 from Wayne A. Brewer of SHCR to R.M. Monti of PONYA (WTCI-87-I)	205
15	Internal Laclede Steel Company memo dated March 18, 1969 from David B. Neptune to R.D. Bay (part of WTCI-82-I)	207
	Section 3.5 – Stud Shear Connector Tests	
16	Letter dated November 3, 1969 from James White of SHCR to Lester S. Feld of PONYA (part of WTCI-253-L)	208
17	Contract dated January 6, 1970 from Guy F. Tozzoli of PONYA to Roger G. Slutter of the Fritz Engineering Laboratory, Lehigh University (part of WTCI-253-L)	210

3M

GENERAL OFFICES • 2501 HUDSON ROAD • ST. PAUL, MINNESOTA 55119 • TEL. 733-1110

Industrial Tape Division

June 22, 1967

Dr. Peter Chen
Skilling, Helle, Christiansen & Robertson
230 Park Avenue
New York, New York

Dear Peter:

Attached are two copies of a report explaining the results of our tests on full size dampers. I trust these will reach you in adequate time for your study before our meeting next Tuesday, June 27, 1967, in St. Paul.

Very truly yours,

Don

D. B. Caldwell
Project Engineer
Acoustic Products

I. Introduction

Vibrational motion of tall buildings and structures can be damped out by the employment of dampers as non-load carrying elements in the structure.

Most of the dampers are designed so that they convert part of the mechanical energy into heat and thus reduce the amplitude of motion. The medium in which this transfer of energy takes place is generally either a viscoelastic material or liquid.

In this report we discuss only a particular damper employing a viscoelastic material as the damping medium.

II. Damper Shape and Desired Characteristic

In general the damper is comprised of two viscoelastic layers bonded between three rigid surfaces, planar on at least one surface (Figure 1).

The damper will be placed such that the application of the load generates shear deformation in viscoelastic material such as shown in Figure 1.

Due to specific requirements of the World Trade Center, the dampers should meet the following requirements within the temperature range 72-78°F and up to 50% R.H. (see technical specification).

a. Average Stiffness

The damper should have a total average stiffness of at least 12,000 lbs. axial load at the specified frequency of 0.1 C/sec. and at a deflection of 0.02".

b. Average Loss Factor (tan δ)

The average damping factor or loss tangent should be at least 0.6 at 0.1 C/sec.

c. Fatigue

After 100 cycles at 20×10^{-3} amplitude and 0.1 C/sec. G" shall not decrease by more than 20% when the damper temperature has returned to its initial value (first cycle).

- Page 2

d. Ultimate shear strength

The damper, when loaded in shear should be able to withstand 48,000 lbs. of load - this includes both static plus dynamic load.

e. Static and dynamic deformation

Maximum amplitude of vibration i.e. viscoelastic shear deformation will be around $20x10^{-3}$ inches dynamic and $30x10^{-3}$ inches static.

In order to fullfill the above mentioned requirements a viscoelastic material with the proper dimension was selected. Figure 1 shows the actual damper with all the dimensions.

III. Test Objective and Procedure

a. Test objective

For the purpose of establishing the effectiveness and the efficiency of dampers the following properties were selected for evaluation.

1. G", loss shear modulus as a function of temperature (T) and fatigue cycle (N).

2. W_1 and W_{100} and W_t, work done in the first and one hundreth cycles and total work done in 100 cycles respectively.

3. Temperature rise accompanying fatigue (100's and 1000 cycles).

4. Loss tangent as a function T and N.

5. G' and G* storage and complex shear modulus as a function of T and N.

6. Total heat production in viscoelastic material.

7. Ultimate shear strength.

b. Test procedure

Twenty-two full size dampers were prepared for testing. For the purpose of monitoring the temperature of viscoelastic material in the damper a thermocouple was imbedded in the center of viscoelastic part as shown in Figure 2.

The shear deformation was detected by an L.V.D.T. which was attached to the damper in such a way that the coil of the L.V.D.T. was rigidly fastened to the stationary part of the damper while the core was clamped to the moving part of the damper, when cyclic load was applied, as shown in Figure 2.

Tests were carried out at two different locations and on two similar closed loop-feed back machines. Four dampers were tested at M.T.S. Corporation in Minneapolis and 18 samples were evaluated at Materials Research Laboratory Inc. in Chicago.

The testing environment, as far as temperature and humidity control is concerned, was not ideal.

In general the following test procedures were followed at both laboratories.

The damper was rigidly mounted, between the machine ram and the load cell and the L.V.D.T. was connected through ram control panel to the X axis of an X-Y chart recorder. The output of the load cell was made to drive the Y axis of the chart. By the use of micrometer head (Figure 2) the L.V.D.T. was calibrated so that one inch of chart in the X axis represented .004 inches of shear deformation. Load cell was also calibrated electronically such that one inch of chart was equivalent to 4000 pounds in the case of MTS machine and 5000 pounds for MRL machine.

Temperatures were recorded by the use of two TC's and a two channel recorder in which one channel recorded viscoelastic temperature and the other monitored the environment temperature. An ice bath was used as a temperature reference point.

The machines were set on strain control. Signal from L.V.D.T. was compared to a preassigned signal from function generator which was set on sine function with 20×10^{-3} inch maximum amplitude and .1 C/sec frequency.

Before the start of test run the recorder was calibrated and the output of both TC 1 and TC 2 were recorded. Tests were conducted on each damper for 1 to 100 cycles and in one special case a 1000 cycle test was performed. After a 100 cycle test the damper was left to cool down and tested at the initial (first cycle) temperature.

IV. Analysis of Test Results

The results obtained from these tests were in the form of hysteresis loops (H.L.) - force vs. displacement as shown in Figure 3. Assuming that the linear viscoelastic theory is applicable to this case, the relationships between dynamic properties of damper for the case of controlled **sinusoidal** displacement of the form

$$\ell = \ell_0 \operatorname{Sin} \omega t$$

are as follows:

$$\gamma = \gamma_0 \operatorname{Sin} \omega t \qquad 1$$

$$\sigma = \sigma_0 \operatorname{Sin} (\omega t + \delta) \qquad 2$$

$$G'' = \frac{\sigma_0}{\gamma_0} \operatorname{Sin} \delta \qquad 3$$

$$G' = \frac{\sigma_0}{\gamma_0} \operatorname{Cos} \delta \qquad 4$$

$$D = \tan \delta = G''/G' \qquad 5$$

$$G^* = (G'^2 + G''^2)^{1/2} \qquad 6$$

$$W_1 = \pi G'' \gamma_0^2 V \qquad 7$$

where;

ℓ = dicplacement (in.)

ℓ_0 = maximum displacement (in.)

ω = angular velocity (rad/sec)

t = time (sec)

σ = shear stress (psi)

σ_0 = maximum shear stress (psi)

$\gamma = \ell/T$ = shear strain (in./in.) T = thickness of v.e. material (in.)

$\gamma_0 = \ell_0/T$ = maximum shear strain (in./in.)

G', G" and G* = storage, loss and complex shear modulus (psi)

D = $\tan\delta$ = loss tangent

W_1 = dissipated energy in one cycle (in-lb.)

V = $2A_vT$ = total volume of v.e. material (in^3)

A_v = viscoelastic shear area (in^2)

The areas of H.L.'s were measured by a planimeter and the dissipated energy in one cycle, W_1 was calculated as follows:

$$W_1 = A_p C_1 C_2$$

where

A_p = area of the H.L. (in^2)

C_1 = force scale factor (lbs/in)

C_2 = displacement scale factor (in/in)

knowing the total volume of viscoelastic material V and also the maximum strain γ_o the value of G" can be readily calculated from Equation 7 i.e.

$$G'' = W_1/\pi\gamma_o^2 V$$

By substituting G" in Equation 3 $\sin\delta$ and consequently $\tan\delta$ is calculated i.e.

$$\tan\delta = \frac{G''\gamma_o}{[\sigma_o^2 - (G''\gamma_o)^2]^{1/2}} = \frac{W_1}{[(\pi\gamma_o\sigma_o V)^2 - W_1^2]^{1/2}}$$

also from Equations 5 and 6 we obtain G' and G*.

Ultimate shear strength were measured on a 60,000 lbs. capacity universal testing machine, and during testing load-deflection was recorded.

Calculations were also made in regard to heat generation and subsequent storage and dissipation of heat. Total heat generated was obtained by assuming a linear relationship between dissipated energy W and the number of fatigue cycles, N.

From this linear relationship the total energy dissipated in 100 cycles will be

$$W_{total} = \frac{W_1 + W_{100}}{24} \times 100 \quad \text{ft-lb}$$

and the heat generated Q_t is

$$Q_t = W_{total}/778.2 \text{ BTU}$$

The total heat generated Q_t can be divided into two parts, 1) heat stored in the viscoelastic material, Q_s and 2) heat dissipated through conduction, convection and radiation to other parts of the system, Q_d i.e.

$$Q_t = Q_s + Q_d \qquad 9$$

Since we measured the temperature rise and also know the physical properties such as density and specific heat of the viscoelastic material, Q_s can readily be calculated. The following formulas were used in this analysis.

$$Q_s = M_{ve}C\Delta T \qquad 10$$

$$Q_t - Q_s = Q_d$$

Tables 1 to 4 represent the numerical results and Figures 4 to 7 represent the graphical presentation of these results.

V. Conclusion

Although the number of test runs on full size dampers are insufficient for a precise statistical analysis, nevertheless the following conclusions can be drawn from the results.

G" and consequently energy dissipation per cycle W are inversly proportional to temperature. The relationship seems to be approximately linear. The relationship of temperature rise to fatigue cycle is also, for the first one hundred cycles, approximately linear, but due to the fact that most of the generated heat is dissipated to the environment, it seems that after 400 cycle (see results on 1000 cycle test) a steady state is approached. It is therefore safe to assume that G" or W per cycle remain relatively constant afterwards.

The effect of temperature on loss tangent in this range (70-82°F) seems to be negligible although a slight increase in loss tangent with temperature is noticable (Figure 6).

It should be observed that the temperature in the v.e. material was measured in a transient state and the actual temperature in the v.e. material was possibly slightly higher than those shown, but the difference cannot be more than 1.0° or at most 1.5°F.

Test Program

for

World Trade Center Viscoelastic Damping Units

Proposed by

Stephen H. Crandall

May 20, 1968

2

1. Test Samples

Fifty-two sample damping units shall be fabricated and delivered to the Acoustics and Vibration Laboratory, Room 5-024, M.I.T. These units shall be identical to those which are to be supplied for installation in the World Trade Center towers under Contracts WTC-219.00 and WTC-224.00, except that each test sample shall have one thermocouple embedded in the viscoelastic material. The thermocouple specifications shall be delivered to Professor Crandall.

The test samples shall be numbered according to a random pattern and ten of the units shall be sent to the Port of New York Authority for storage and subsequent testing for aging effects.

2. Test Objectives

The major portion of the test shall be devoted to determining the statistical distribution of the following basic mechanical properties of the damping units:

Loss factor for steady cycling at 0.1 Hz.

Dynamic stiffness for steady cycling at 0.1 Hz.

Ultimate load when deformed at the rate of 0.5 in. per min.

Ultimate displacement when deformed at the rate of 0.5 in. per min.

Thirty samples shall be tested to determine these properties. Before beginning these tests four samples shall be cycled for 10,000 cycles (if failure does not occur earlier) to determine the possibility of fatigue failures for the dampers. If fatigue failures do occur in these four samples, it will be proposed that some of the thirty samples for the basic statistical tests be used to obtain additional fatigue information (after loss factor and dynamic stiffness measurements have been made). These samples will not then be available for the ultimate load test under deformation at the rate of 0.5 in. per min. The decision as to how many samples to divert to fatigue testing in this manner shall be made by Professor Crandall in consultation with all interested parties.

In addition to the fatigue test and the basic test for statistical distribution, supplementary tests shall be made on the remaining eight samples to obtain additional engineering information concerning the behavior of the damping units. These supplementary tests are designed to elicit information on how the energy absorbtion of a damper is affected by:

(i) Preload on the damper.

(ii) Preliminary high frequency cycling.

3. Test Facilities

All cycling tests shall be performed on a special test frame in which one or two damping units can be cyclically deformed as the structure is sheared by a motor-driven eccentric. The test frame shall simulate the average local elasticity of the damping-unit connectors in the World Trade Center towers. The amplitude of the test-frame deformation shall be controlled by the size of the eccentric. The amplitude of the damping unit deformation depends on the dynamic stiffness of the damping unit and will vary from element to element and will vary with temperature for any one element. Damping unit test amplitudes shall be specified in terms of an equivalent amplitude measured on a steel dummy unit whose stiffness is 650,000 pounds per inch. The frequency of the cycling shall be controlled by the choice of sprockets in the chain drive between the motor-driven reducer and the eccentric drive-shaft. Forces in the damping units shall be measured by strain-gage load cells and deformations of the units shall be measured by L.V.D.T.'s. Force-displacement curves shall be recorded on an on-line X-Y plotter. The special test structure shall be disassembled at the conclusion of the tests and sent to the New York Port Authority for storage.

The ultimate load tests shall be performed on a manually operated hydraulic testing machine with a capacity of 100,000 pounds. The instrumentation shall be the same as in the cycling tests. The operator shall endeavor to maintain the rate of deformation at a nearly uniform rate as close as possible to 0.5 in. per min. The actual rate of deformation shall be recorded.

4. Specifications for Fatigue Tests

These tests on four units chosen at random shall be performed prior to the basic statistical tests described in Section 5 below.

(a) The cycling rate shall remain within ± 2% of a fixed value lying within the range from 0.08 to 0.11 Hz (4.8 to 6.6 cycles per minute).

(b) The mean load on the damping unit during a cycle shall be zero.

(c) The cyclic amplitude of the test-frame displacement shall remain within ± 2% of a fixed value lying within the following ranges.

(i) Two damping units shall be tested with equivalent amplitudes in a range from 0.018 to 0.022 inches.

(ii) Two damping units shall be tested with equivalent amplitudes in the range from 0.027 to 0.033 inches.

(d) The ambient temperature and humidity and the temperature of the viscoelastic material shall be recorded at hourly intervals during the fatigue tests.

(e) Force-displacement curves for each specimen shall be recorded by an on-line X-Y plotter at hourly intervals during the fatigue tests. Clocktime and cycle number shall be noted.

(f) If at the end of 10,000 cycles a unit has not obviously failed and its force-displacement curve has not altered dramatically the cycling shall be stopped and the unit shall be removed from the cycling test structure and placed in the ultimate-load test machine. There it shall be subjected to an approximately uniform rate of deformation as near to 0.5 in. per min. as possible. Force and displacement shall be recorded until failure occurs.

If all four units survive 10,000 cycles and if their subsequent ultimate loads are each greater than 35,000 pounds it shall be concluded that fatigue is not a serious hazard and no further considerations shall be given to fatigue in this test program.

If, however, one or more of the four units fail to meet the above requirements, it shall be necessary to consider very carefully whether additional fatigue testing should be carried out. Such additional fatigue tests would be carried out (on random samples from the 30 basic statistical test-samples) in lieu of the ultimate-load test.

6

5. Specifications for Basic Statistical Tests

These tests shall be performed on thirty specimens. To determine dynamic properties of the damping units under uniform cycling each sample shall by cycled for 100 cycles at a uniform rate. The sample shall then be allowed to cool down to its initial temperature before going through two additional cycles. Force-displacement curves and temperature data shall be recorded as described below. After the cycling test each sample shall be deformed to failure in an ultimate-load test (if additional fatigue testing is decided upon, some fraction of the samples shall be given fatigue tests in lieu of ultimate load tests).

The following specifications apply to the tests for dynamic properties under uniform cycling.

(a) The cycling rate shall remain within ± 2% of a fixed value lying with the range from 0.08 to 0.11 HZ (4.8 to 6.6 cycles per minute).

(b) The mean load on the damping unit during a cycle shall be zero.

(c) The cyclic amplitude of the test-frame displacement shall remain within ± 2% of a fixed value lying within the following ranges.

(i) Twenty units shall be tested with equivalent amplitudes in the range from 0.018 to 0.022 inches.

(ii) Ten units shall be tested with equivalent amplitudes in the range from 0.027 to 0.033 inches.

(d) The ambient temperature and humidity and the temperature of the viscoelastic material shall be recorded for the 1^{st}, 10^{th}, 20^{th}, 50^{th}, 100^{th} and 101^{st} cycles for each specimen.

(e) Force-displacement curves shall be recorded by an on-line

X-Y plotter for the 1st, 2nd, 10th, 20th, 50th and 100th cycles for each specimen. At the end of the 100th cycle, the deformation shall be suspended until the viscoelastic material returns to its initial temperature, plus or minus 0.2° F. The time required to reestablish the initial thermal condition shall be recorded. Then cycling shall be resumed for an additional two cycles. Force-displacement curves for cycles 101 and 102 shall be recorded.

The following specifications apply to the ultimate-load test.

(f) The damping units shall be transferred from the cyclic-test frame to a 100,000 pound hydraulic test machine. Half of the units shall be tested in tension and half in compression.

(g) Ambient temperature and humidity and the temperature of the viscoelastic material shall be recorded at the beginning of each ultimate-load test.

(h) The testing machine shall be manually controlled to provide a nearly uniform rate of deformation as near as possible to 0.5 inches per minute.

(i) Force-displacement curves to failure shall be recorded on an on-line X-Y plotter. The time history of displacement shall also be obtained.

(j) Failure modes shall be noted and photographed where informative.

6. Supplementary Tests

Four specimens shall be tested to investigate the effect of preload on the energy absorbtion of the damping units. These tests shall be similar to the cycling portion of the basic test with the exception that instead of cycling about a mean load of zero the cycling shall take place around non-zero tensile and compressive loads.

The specifications for the preload test are given below.

(a) The cycling rate shall remain within ± 2% of a fixed value lying with the range from 0.08 to 0.11 Hz (4.8 to 6.6 cycles per minute).

(b) The damping units shall be inserted into the test frame in such a manner that the mean deformation of the element during the cycle takes on the following values.

(i) One unit shall be tested with a cyclic mean equivalent elongation in the range between 0.009 and 0.011 inches.

(ii) One unit shall be tested with a cyclic mean equivalent elongation in the range between 0.018 and 0.022 inches.

(iii) One unit shall be tested with a cyclic mean equivalent compression in the range between 0.009 and 0.011 inches.

(iv) One unit shall be tested with a cyclic mean equivalent compression in the range between 0.018 and 0.022 inches.

(c) The cyclic amplitude of the test frame shall remain within ± 2% of a fixed value which shall produce an equivalent amplitude within the range from 0.018 to 0.022 inches.

(d) The ambient temperature and humidity and the temperature of the viscoelastic material shall be recorded for the 1^{st}, 10^{th}, 20^{th}, 50^{th}, 100^{th} and 101^{st} cycles for each specimen.

(e) Force-displacement curves shall be recorded by an on-line X-Y plotter for the 1^{st}, 2^{nd}, 10^{th}, 20^{th}, 50^{th}, and 100^{th} cycles for each specimen. At the end of the 100th cycle, the deformation shall be suspended until the viscoelastic material returns to its initial temperature, plus or minus 0.2° F. The time required to reestablish the initial thermal condition shall be recorded. Then cycling shall be resumed for an additional two cycles. Force-displacement curves for cycles 101 and 102 shall be recorded.

Four specimens shall be tested to investigate the effect of higher frequency cycling on the energy absorbtion of the damping units. Each specimen shall by cycled for ten cycles at the standard amplitude and frequency. Then the frequency shall be increased and the amplitude decreased (or left unchanged) and the units cycled for 100 cycles before returning to the standard amplitude and frequency. Force-displacement curves shall be recorded before and after the high frequency cycling as described below.

Specifications for the high-frequency test are given below.

(f) All four specimens shall be cycled for ten cycles at a fixed frequency between 0.08 and 0.11 Hz with an equivalent amplitude between 0.018 and 0.022 inches.

(g) Ambient temperature and humidity and the temperature of the viscoelastic material shall be recorded for the 1st and 10th cycles.

(h) Force-displacement curves shall be recorded on an on-line X-Y plotter for the 1st and 10th cycles.

(i) For two samples the equivalent amplitude shall be decreased to a fixed value within the range from 0.009 to 0.011 inches and the cycling frequency shall be increased to

(i) A value between 0.23 and 0.27 Hz for one sample.

(ii) A value between 0.46 and 0.54 Hz for one sample.

For the other two samples the equivalent amplitude shall be maintained within the range 0.018 to 0.022 inches and the cycling frequency shall be increased to

(iii) A value between 0.23 and 0.27 Hz for one sample.

(iv) A value between 0.46 and 0.54 Hz for one sample.

The specimens shall be cycled for 100 cycles at the higher frequencies indicated.

(j) Ambient temperature and humidity and the temperature of the visco-elastic material shall be recorded at the 1st, 10th, 20th, 50th and 100th high-frequency cycles.

(k) Force-displacement curves shall be recorded for the 1st, 50th, and 100th high-frequency cycles.

(l) The frequency and equivalent amplitude for each specimen shall now be returned to the values established in (f) above. The time elapsed while making this change shall be noted. The specimens shall then be cycled for ten cycles as in (f). The measurements in (g) and (h) shall be repeated.

7. Report of Test Results

The dynamic characteristics of the viscoelastic damping units as determined by these tests shall be reported as follows. For each of the parameters listed below a statistical distribution diagram shall be given along with values for the mean and standard deviation.

(a) For the first and one hundred and first cycles of steady cycling at nominal frequency of 0.1 Hz and nominal equivalent amplitude of 0.02 inches (and 0.03 inches) the following parameters.

(i) Dynamic stiffness

(ii) Loss tangent

(iii) Energy dissipated

(b) For ultimate testing at a nominal rate of displacement of 0.5 inches per minute (tension and compression) after previously enduring 102 cycles at nominal frequency of 0.1 Hz and nominal equivalent amplitude of 0.02 inches (and 0.03 inches) the following parameters.

(i) Ultimate strength in pounds

(ii) Ultimate deformation in inches

The results of the fatigue investigation shall be described. Either the ability of these units to endure repeated loadings shall be verified or an S-N type diagram shall be given.

The results of the preload investigation shall be described. The energy absorbtion capabilities of a preloaded damping unit shall be graphically compared with that of a unit without preload. The results of the high-frequency cycling test shall be described. The energy absorbtion of a damping unit before and after high-frequency cycling shall be graphically compared.

An analysis shall be made of the effects of ambient temperature and element temperature on the dynamic characteristics of the damping units. Graphs shall be plotted of actual element displacement, cyclic energy loss and loss tangent as a function of element temperature.

In addition to giving dynamic characteristics for the damping units separately a discussion shall be given of the cyclic test frame and its interaction with the damping units. The force and displacement of the eccentric driver shall be recorded for certain cases so that the total energy input to the frame can be compared with the loss in the damping units.

All original X-Y plots. with necessary identification shall be included in the report.

Test of Viscoelastic Damping Units
for World Trade Center Tower Buildings

by S. H. Crandall
L. E. Wittig

Summary

Tests have been performed on 39 samples of the viscoelastic damping units proposed by 3-M for the World trade Center Towers to determine the distribution of their mechanical properties and to ascertain their effectiveness under a range of off-design operating conditions. It was found that although there is considerable variability of properties from unit to unit in a batch and from one batch to another, the energy absorbing capabilities of the elements are generally adequate to provide the expected damping under design conditions and that the elements do perform satisfactorily under limited variations of: loading conditions; speed of oscillation; duration of oscillation and ambient temperature.

TABLE OF CONTENTS

I. Introduction

In order to control the tendency of the World Trade Center Towers to sway under the action of high winds it is planned to increase the inherent structural damping of the buildings by attaching viscoelastic damping elements at the major structural joints connecting floors and columns. The damping elements are bolted between the columns and the lower members of the floor trusses in such a way that the elements are forced to elongate (or shorten) whenever the buildings sway. These damping elements have been designed by Skilling, Helle, Christiansen and Robertson (SHCR) and fabricated by Minnesota Mining and Manufacturing Company (3-M). See Reference [1] for background information and the results of tests by 3-M on 22 prototype units. The present series of tests has been conducted to supplement and to serve as an independent check on these earlier tests.

Twenty units were tested according to a basic or standard test which closely paralleled the earlier 3-M tests. The standard test consists of two parts: a cycling test and an ultimate test. In the cycling test an element's elongation and force is monitored for 100 cycles as it undergoes simple harmonic motion at the design amplitude and frequency. From these measurements it is possible to evaluate the following important mechanical parameters for the elements: the dynamic stiffness k (kips/inch), the energy dissipated per cycle W(inch-lbs) and the loss tangent, tan ϕ, and to observe how these parameters change during a period of steady cycling which lasts for 100 cycles (16.7 minutes for the design frequency of 0.1 Hz). In the ultimate test the element is stretched (or compressed) at the steady rate of 0.5 inches per minute until failure occurs. The elongation and force history are monitored and the ultimate values of each are recorded.

-3-

In addition to the standard test, 19 additional tests were performed to investigate the endurance capabilities of the elements and to investigate their operation under conditions different from the design conditions prescribed in the standard tests. The conditions tested included variations in amplitude and frequency, variations in ambient temperature and the effect-of-superposing a static preload on the simple harmonic loading employed in the standard cycling test.

The principal differences between the standard cycling tests of this report and those of reference [1] arise from the differences in test facilities. The tests of Reference [1] were performed in a servo-controlled testing machine which maintained a fixed (single) amplitude of 0.020 inches throughout the test. The tests described herein were performed in a specially built test frame (see Fig. 1) which was intended to simulate the structural environment which the elements will see when they are fastened in place in the World Trade Center Towers. During the test the frame is periodically sheared by a motor driven eccentric (see Fig. 2). The amplitude of the frame shear is controlled by the "throw" of the eccentric. The damping element under test (see Fig. 3) is forced to expand and contract as the frame is sheared. The element elongation amplitude depends on the relative stiffness of the frame and of the element itself. The precise relation is somewhat complicated and is developed in Appendix A. It is sufficient here to realize that for the same frame shear (same sized eccentric) the element elongation amplitude for a soft element will be greater than for a stiff element.

In order to describe the frame shear in a meaningful way the elongation amplitude of an aluminum alloy "dummy" element (see Fig. 4) with a

-4-

stiffness of 600 kips/inch was measured and c[illegible]e equivalent amplitude. During the actual tests the elongation amplitude for the visco-elastic elements were greater or less than the equivalent amplitude depending on the stiffness of the element under test. Three different sized eccentrics were employed. The standard tests were performed using an eccentric which produced an equivalent amplitude of 0.019 inches. The other eccentrics produce equivalent amplitudes of 0.010 inches and 0.023 inches. The frequency of cycling during the standard tests was approximately 0.1 Hz (actually 0.0989 Hz). This corresponds to a period of 10 seconds per cycle (actually 10.11 seconds per cycle). Other tests were also run at two and a half times this frequency, and at five times this frequency.

II. Description of Tests

A. Test Frame

All cyclic tests were performed on a special test frame (see Fig. 1). This special frame was constructed for these tests because it was felt that the damping units should be tested in a structural environment similar to that in which the dampers will be installed in the World Trade Center Towers. The test frame allows the damping units to deform more naturally than they would deform if tested in a standard testing machine. For example, the damping units tend to rotate somewhat when they are elongated in either the test frame or in their building environment. A standard testing machine, however, would not allow such rotational motion. The test frame also permitted us to check the effect of small misalignments in the installation of the dampers.

The test frame is goemetrically quite similar to the truss-outer wall portion of the buildings. Damping units are held in the test frame

-5-

with 1-inch diameter A490 bolts in single shear on one end and with 7/8 inch diameter A325 bolts in double shear on the other end, corresponding to their installation in the buildings. A 1300 ft-lb. impact wrench was used to tighten the bolts (see Fig. 5) according to turn-of-the-nut regulations [2]. The main requirement of these regulations is that after the nut has been brought up tight with a hand wrench the power wrench is applied to turn the nut through an additional 180°. New bolts were used for each test and shim material was used when needed for proper alignment.

When testing the damping units, the whole test frame was deformed sinusoidally by a motor driven eccentric (see Fig. 2). The equivalent amplitude referred to in the various tests is the elongation amplitude that a lossless elastic member with a stiffness of 600,000 lbs./in. would experience if it were to be bolted into the test frame instead of a damping unit (a more complete discussion of the stiffness of the test frame and its affect on the elongation amplitude of a damping unit is given in Appendix A).

The test frame was located in a temperature controlled room. The temperature and humidity were recorded during all tests. For all tests, except when specially noted, the temperature has held at 75°F ± 3°F.

B. Standard Cycling Tests

The most common test that was performed is referred to as the standard statistical test. This test was carried out on the test frame described above. The equivalent amplitude during this test was 19 mils (one mil equals 0.001 inches); the period per cycle was 10.11 seconds. The standard test was intended to be somewhat similar to tests performed by 3M Company so that our results could be compared to their results.

-6-

During a standard test the damping units were cycled 100 times and data was taken on the 1st, 2nd, 10th, 20th, 50th and 100th cycles. The units were then allowed to relax for 20 minutes and more data was taken on the 101st and 102nd cycles.

Damper extensions and contractions were measured with an LVDT (linear variable differential transformer).. The LVDT was mounted as shown in Fig. 3 so that the total motion between the two ends of the damper was measured along the central axis. It should be noted that in this respect these tests differ from those of 3-M where only the relative motion between two internal points within the damper was measured. The axial force applied to the damper was measured with a strain gage dynamometer located in the angles that connect the dampers to the truss. The temperature of the viscoelastic layer was monitored by a thermocouple embedded in the viscoelastic material. The LVDT and the force gage were calibrated for each test.

Outputs from the LVDT and the force gage were fed into the same x-y recorder shown on the left of Fig. 6. Because of the viscoelastic behavior of the damper there is a phase shift between the force signal and the elongation signal. The phase shift causes the force-elongation plot to form a closed hysteresis loop during each cycle of oscillation. The area of the loop is directly proportional to the energy dissipated during the cycle. The loss factor and the dynamic stiffness of the damper can also be determined from this plot. The output from the thermocouple was fed into a second x-y recorder shown in the right in Fig. 6 and plotted as a function of time.

During one test the rotational motion of the damper and the moment applied to the damper were measured. From this information the amount of energy absorbed by the damper due to rotational motion was calculated.

-7-

C. Special Cycling Tests

Besides the standard statistical tests, some additional cyclic tests were performed to determine further properties of the damping units. Four different types of tests were carried out: (i) endurance tests, (ii) preload tests, (iii) higher frequency tests, and (iv) one endurance test at an elevated temperature.

The purpose of the endurance tests was to check the fatigue life of the damping units. These tests were quite smmilar to the standard tests described earlier except that the total number of cycles was much greater. Two tests were run with an equivalent amplitude of 10 mils for 10,000 cycles, and two tests were run with an equivalent amplitude of 19 mils until fatigue was noticed.

The preload tests were performed by bolting the damping units into the test frame when the frame was slightly deformed from its neutral position. This procedure forces the damper to oscillate about a nonzero mean displacement. Such a condition could easily arise in the World Trade Center Towers if the swaying oscillation took place about a static sway due to the steady state wind components. These tests were also performed in a manner similar to that of the standard test. However, during the four preload tests the mean equivalent pre-elongations were approximately ± 10 mils and ± 20 mils.

The higher frequency tests were conducted to see if oscillations at frequencies corresponding to the higher modes of the buildings would cause any deterioration in the effectiveness of the dampers. Higher test frequencies were obtained by changing the sprockets of the motor transmission system. During these tests the damper specimens were first cycled 10 times at the standard frequency of 0.1 Hz and at the standard equivalent amplitude of 19 mils. The frequency of the forced oscillation was then changed to either 0.25 Hz or to 0.50 Hz; the equivalent amplitude was either held the same or reduced to 10 mils. The specimens were cycled 100 times under these new conditions. After these 100 cycles the frequency wss returned to 0.10 Hz and the equivalent amplitude was returned to 19 mils. The specimens were cycled 10 more times to see if there was any noticeable change in the damper properties since the original 10 cycles.

The last special cyclic test that we performed was an endurance type test with the exception that the ambient temperature was 10°F above the normal 75°F. The results of this single test were discussed in some detail in a preliminary report which is included here as Appendix D.

D. Ultimate Load Tests

All of the damping units from the standard statistical tests and the endurance tests were subjected to an ultimate load test. The ultimate load test consists of stretching or compressing the dampers until they are physically broken. The purpose of these tests was to see if the specimens still met the acceptance levels established by 3M Company after they had been through the cyclic tests. These tests were performed on a manually controlled hydraulic testing machine with a capacity of 200,000 pounds (Figs. 7, 8). The axial force and elongation of the damper were recorded on an x-y recorder during the test. An additional x-y recorder was used to monitor the rate of axial elongation of the specimen. This rate of axial extension was held as close as possible to 0.5 inches per minute. Half of the specimens from the standard statistical tests were broken in tension and half were broken

-9-

in compression. All of the specimens from the endurance tests were broken in tension. The grips for these tests used 1 inch diameter A490 bolts in single shear at one end of the specimen and 7/8 inch diameter A325 bolts in double shear at the other end. From the recorded results statistical information on the ultimate loads and the ultimate extensions of the dampers has been obtained.

III. Results of Tests

A. Standard Statistical Tests

The major portion of this test program was devoted to measuring some basic mechanical properties of the damping units. The damping unit'properties that were obtained are their loss factor, dynamic stiffness, ultimate load, and ultimate extension. The amount of energy dissipated per cycle by the dampers and the amplitude of the periodic displacement between the ends of the damping units was also measured. Statistical distribution curves for the dynamic stiffness, loss factor, energy absorbed per cycle and the amplitude of the periodic displacement are given in Figures 9, 10, 11 and 12. The results of the ultimate load tests are discussed in Section III-C. For sake of comparison, results of tests conducted by 3M Company are included in the same figures.

The data used for the statistical information of this investigation was taken from measurements made during the tenth cycle of oscillation. Hysteresis loops recorded during first and second cycles were usually not closed, and therefore, data from these first two cycles is not as accurate as data from the tenth cycle. Also, since it is quite probable that oscillation of the Trade Center Towers will occur in groups of several cycles (this is typical of narrow band random vibration), we feel that the tenth cycle information is more meaningful. The results of tests

-10-

conducted by 3M Company were taken from tables in Reference 1. For the dampers they tested, we plotted the results corresponding to the first test on each individual damper that was tested at an ambient temperature of 75°F ± 3° F. Nineteen of their tests fell in this category.

The mean value and the standard deviation for each of the damper properties are listed along with their distribution curves. The most important single parameter is W the energy loss per cycle. In our opinion the average value W = 574 inch. lbs. (with a standard deviation of 72 inch. lbs.) is satisfactory for the proposed application. It may be noted that the mean values of dynamic stiffness and loss factor that we measured (i.e., 555 kips/inch and 0.836 respectively) are above the levels (400 kips/inch and 0.7 respectively) stated in the Qualification Requirements [3]. The spread of the distributions about the mean is quite large. In the case of the loss factor the standard deviation (0.168) is sufficiently large that had these dampers been representative of the samples used to determine Acceptance [3] there is a good chance that the initial sample would not meet the manufacturing control limit for loss factor.

As was mentioned earlier, the output signal from a thermocouple imbedded in the viscoelastic material was also recorded. The results of this measurement unfortunately were usually somewhat erratic. Some temperature data did make sense insofar as it showed a gradual increase in the temperature of the viscoelastic layer as the test progressed (see for example the records of damping specimen No. 19 included in Appendix B). In general, however, most of the records were not useful. The reason for this may be that some of the thermocouples were in actual physical contact with the metal of the damping units, whereas others were not.

Originally we had planned to run the 101st and 102nd cycle of the standard test after the thermocouple indicated that the specimen had returned to room temperature. Because of the difficulties with the thermocouple we decided to let the specimen recover for twenty minutes. before running the last two cycles. Twenty minutes was chosen because it was the approximate duration of the first 100 cycles of the test.

All of the thermocouple records displayed a periodic pattern. They show that the viscoelastic layer both heats up and cools down once during each full cycle of oscillation. This behavior was at first rather surprising. We expected that the record would show two peaks per cycle instead of just one. Two peaks would occur if the viscoelastic layer could not tell a positive shear from a negative shear. The probable explanation for the observed behavior is that the viscoelastic material is anisotropic - i.e., its properties are a function of direction.

Figure 13 shows how the properties of a typical damping unit change during a standard test. In general the stiffness of the element tends to decrease while the energy dissipated per cycle, the loss tangent, and amplitude of displacement all tend to increase. After a 20 minute rest (cycles 101 and 102) the element properties have shown a recovery in the direction of their original values. We computed the average fatigue loss between the 10th and 100th cycles of the standard tests and found it to be about 11%. The fatigue loss is the percentage change in the loss modulus G". It is also equal to the percentage change in W/δ^2 where W is the energy loss per cycle and δ is the elongation amplitude.

From bending moment measurements made while testing specimen No. 1, the energy dissipation due to rotational motion of the damper was calculated to be about 19% of the dissipation due to axial motion.

-12-

The effect of misaligning the damper specimen in the test frame was also investigated. Misalignments of the order of 1/4 inch, so that the dampers can be easily pushed into place by hand, appear to have a negligible affect on the amount of energy which the dampers absorb.

For the benefit of future users of the test frame, a sample of the data reduction for a standard test has been included in Appendix B.

B. Special Cycling Tests

Four different endurance tests were conducted. Two of these tests were run with an equivalent amplitude of 10 mils, and two were run with an equivalent amplitude of 19 mils. The results of a low amplitude test are shown in Figure 14. As can be seen, the properties of the damping element did not change appreciably in the course of 10,000 cycles. The properties did fluctuate somewhat, but this was probably due to small changes in the ambient temperature. During the second low amplitude endurance test, the frequency of oscillation was increased so that the total rate of energy dissipation would be about the same as it was during the high amplitude endurance tests. Even after this higher rate of energy dissipation the specimen did not appear to be damaged.

The results of a high amplitude (19 mils equivalent amplitude) endurance test are shown in Figure 15. These results show that there is some definite damage to the damper at about the 1000th cycle. This test was probably too severe. SHCR estimate that on the average there will be only 15 cycles a year with amplitudes greater or equal to to amplitude used in this test. Furthermore, the test frame used in these tests tends to overstretch the damper when it softens (see Appendix A). For the above reasons it appears that chances of fatigue failure of the dampers are unlikely.

All of the tests conducted for this report were made with the assembly bolts of the dampers in a finger tight condition. After the element mentioned above had fatigued, we found that tightening the assembly bolts seemed to restore some of the life of elements. Also, we found that if the assembly bolts were only finger tight before the element was bolted into the test frame, then vibration caused by the impact wrench completely loosened them. For these reasons we highly recommend that the assembly bolts of the damping units be kept tightened at all times. We also checked to see if tightening the assembly bolts affected the amount of energy dissipated by the dampers, and found that tightening them decreased the energy dissipated about 10%.

The preload tests indicated that forcing the dampers to oscillate about a nonzero mean displacement does not appear to reduce their effectiveness. The average energy dissipated during the 10th cycle of the preload tests was 581 in. lbs., whereas the average energy dissipated during the 10th cycle of a standard test was 574 in. lbs.

Figure 16 shows the results of a typical high frequency test. The overall results of the high frequency tests demonstrate that intermediate oscillations at higher frequencies do not appear to change the effectiveness of the dampers at the standard frequency of 0.1 Hz.

Besides the tests discussed above, a few other tests were performed. One series of tests that is of some interest is a set of three 100 cycle tests at an equivalent amplitude of 23 mils on damping unit No. 3. At the end of the third test some definite changes in the damper properties were noticed. The results of these tests are included in Appendix C.

C. Ultimate Load Tests

The results of a typical ultimate load test are shown in Figures 17 and 18. The curves which are shown are for an element that was tested in tension. Two peaks appear in the load-elongation curve (Fig. 17) because after one side of the element separated the other side continued to load for a while longer. The displacement vs. time curve (Fig. 18) shows that the rate of elongation was quite close to the desired 0.5 inch per minute.

Statistical distribution curves for the ultimate loads and ultimate extensions of dampers from the standard statistical tests are shown in Figures 19 and 20. The results of 13 tests conducted by 3M Company and reported in Reference 1 are also shown.

It may be noted that the average ultimate load (47.7 kips) that we measured is greater than the value (45 kips) stated in the Qualification Requirements [3]. The spread of the distribution is quite large. The standard deviation (9.3 kips) is sufficiently large that had these dampers been representative of the samples used to determine Acceptance [3] there is a good chance that the initial sample would not meet the manufacturing control limit for ultimate shear strength. In our tests half of the units were broken in tension and half were broken in compression. The average ultimate load for the tension units only was 51.0 kips and the average ultimate load for the compression units only was 44.4 kips. The average for both tension and compression was 47.7 kips.

The most common mode of failure for the specimen was separation at the bond between the metal and the viscoelastic material. All of the elements that were tested in tension, and about half of the elements tested in compression, failed in this manner. Another mode of failure that occurred during the compression tests was for the viscoelastic bond to break on one side of the element and then for the other side of the element to buckle (Fig. 21). Only one element that was tested buckled

-15-

on both sides. The buckling and the breaking of the viscoelastic bonds were the only modes of failure that occurred.

Ultimate load tests were also conducted on the elements from the endurance test. The two elements from the low amplitude (10 mils equivalent amplitude) endurance tests both broke at loads that were slightly higher than the average ultimate load of 47,700 lbs. However, the two elements from the high amplitude (19 mils equivalent amplitude) endurance tests broke at loads of 22,000 lbs. and 14,000 lbs. which is considerably lower than average. This further verifies that prolonged cycling of the damping units at high amplitudes does result in permanent damage.

IV. Conclusions

The most important characteristic of the damping elements is their capacity to absorb energy under oscillations at amplitudes and frequencies which are probable for the World Trade Center Towers. Ideally they should absorb adequate energy no matter when the oscillations occur or what the ambient conditions are during the oscillations. In our tests we have not been able to cover all possible operating conditions but we have shown that this particular batch of elements do absorb an average of W = 574 inch-lbs under standard test conditions with respect to amplitude, frequency and temperature. Furthermore, the energy absorbtion is not significantly impaired by modest variations in amplitude, frequency and temperature.

Our major concern in the beginning centered around the endurance capability of the elements. We found that the elements could withstand 10,000 cycles of 10 mils equivalent amplitude with no indication of permanent damage. At large equivalent amplitudes (19 and 23 mils) we did obtain evidence that prolonged cycling caused a growing breakdown of the bond between the viscoelastic material and the steel which was reflected by a reduction of the element's stiffness and its ultimate load capacity. See data for Specimens No. 3, No. 4 and No. 5. In spite of the alteration of properties which occurs we conclude that the units will provide adequate energy absorbtion for at least 1000 cycles of 19 mils eouivalent amplitude at temperatures in the vicinity of 75°F. When the ambient temperature is in the vicinity of 85°F the bond breakdown is apparently accelerated somewhat. At this temperature (see Appendix D) it appears that the units will provide adequate energy absorbtion for 500 cycles of 19 mils equivalent amplitude. If present estimates of the number of large oscillations to be expected are not excessively optimistic, it does not appear that there is any real danger of a loss in element effectiveness due simply to the accumulation of cycles of oscillation.

An unknown factor is the effect of aging on the viscoelastic elements. Our tests were completed within a six month period. We had no opportunity to observe any long time deterioration of the elements.

Another unknown factor is the effect of extreme heat or extreme cold on the viscoelastic elements.

When the elements are installed in the towers it is essential that the bolts be tightened meticuluosly. Any slip in the joints would vitiate the usefulness of the dampers. Careful alignment of the element attachment points should be maintained. Our tests indicated that up to 1/4" of misalignment did not affect the energy absorbtion capability of the element. We recommend that the element assembly bolts be tightened with a small hand wrench after installation rather than being left finger-tight. This may decrease the energy absorbed by the element in small amplitude cycles by up to 10 percent but it will serve to protect

-17-

the element against deterioration under large amplitude cycles.

Because of the wide spread in damper properties from batch to batch and from unit to unit within a batch, it is suggested that a program of testing sample units be instituted to check on element parameter values as the various batches are delivered. The most important single parameter is the energy dissipated in a cycle of 10 seconds duration under a known equivalent amplitude. It is this parameter which is directly proportional to the increase in overall tower damping ratio provided by the damping unit. It would be desirable if W, the energy loss per cycle, for 19 mils equivalent amplitude was never less than 400 inch lbs. A desirable average value of W for all batches would be 575 inch lbs. (i.e., about the same as that of the batch reported on here).

V. Suggestions for Further Testing

A program of periodic testing of random samples of installed elements and of the stored unused elements should be instituted. All the endurance tests performed so far have been accelerated life tests. The effect of the passage of years on used or unused elements is still an unknown factor.

The calcualted effectiveness of the dampers depends on the magnitude of the local frame stiffness almost as much as it does on the aamping unit parameters. If the local frame stiffness were only 200 kips/inch instead of the design value of 600 kips/inch (as was the case for the test frame) the energy absorbed by the damper would only be one-fourth of that predicted. In the case of the test-frame this was compensated for by using a larger eccentric. In the actual towers no such compensation is possible. Therefore, it seems imperative to check

-18-

the actual stiffness of the local frame at a few typical damping element locations as soon as possible. If the actual frame stiffness is significantly smaller than the design stiffness the damping units would have to be redesigned. To measure the local frame stiffness one could substitute a turnbuckle and a forcegage for the damping unit and then use the LVDT from the test frame to measure the contraction as the turnbuckle was tightened.

There are a number of tests which would be very interesting to the profession and which would be useful for the benefit of future designers. These are listed below in the order of their desirability.

1) The natural frequencies, damping ratios and mode shapes of the towers should be measured. These can be measured in a few days time by simultaneously recording the outputs of two sensitive seisometers placed at various locations in the buildings and then digitally processing the tapes. Such a service is available from the Structural Sciences Division of Earth Sciences (A Teledyne Company). See literature in Appendix E. The damper oscillation has been designed on the basis of a natural mode and natural frequency computed during the early design of the building and on the basis of an educated guess as to the inherent damping of the towers. A comparison with the measured values would be very informative.

2) Permanent recorders should be installed near the tops of both buildings to monitor the motions (acceleration levels) throughout a period of several years. This would provide valuable feedback for the elaborate wind tunnel and statistical studies which were employed to arrive at the levels of motion used in the design of the damper installation. This would also give the building owner increasing confidence in the sway resistance of his building (if the design is in fact successful and the motion amplitudes remain small).

-19-

There are slow speed tape recorders which go continuously and only need to have the tape changed once every three months, and there are other instruments like strong motion seismographs which remain inactive most of the time and only begin to record when a certain threshold level is reached. See Appendix E for literature.

3) One or two damping units in the towers could be modified so that they could provide force and motion signals at the damper which could be compared with the tower motion. In the simplest modification all that would be necessary would be to replace the pair of angle irons running from the element to truss by the instrumented angle irons from the test frame. The force and elongation signals would provide energy loss loops which permit an estimation of how much damping the viscoelastic units were actually providing. These results would be even more meaningful if the local building frame stiffness had been verified <u>in situ</u> with a turnbuckle as described above.

References:

1. SHCR Report No. DU-1, The World Trade Center Viscoelastic Damping Units, July 17, 1967.

2. Specification for Structural Joints Using ASTM A325 or A490 Bolts. Approved by Research Council on Riveted and Bolted Structural Joints of the Engineering Foundation, September 1, 1966. Endorsed by American Institute of Steel Construction, Inc. Endorsed by Industrial Fasteners Institute.

3. Technical Specifications for Visco-Elastic Damping Units for the World Trade Center, 3786.

-21-

SKILLING - HELLE - CHRISTIANSEN - ROBERTSON

August 29, 1968

Mr. Malcolm P. Levy
Port of New York Authority
World Trade Center Planning
111 Eighth Avenue
New York, New York 10011

Reference: The World Trade Center
MIT Test Program

Dear Mal:

On the afternoon of August 28, 1968, the writer visited MIT to examine the damping unit test rig and to evaluate progress to date.

First, in response to inquiries from MIT, the writer transmitted the following information:

1. All high-tensile bolts must be tightened using the turn-of-the-nut technique.

2. For 1" ASTM A490 bolts, required torque could be 1400 ft-lbs or higher.

3. Washer requirements for ASTM A325 high-tensile bolts are as follows:

   a. With holes 1/16" larger than the nominal bolt diameter, no washers are required.

   b. For all other cases, 7/16" thick plate washers are required under both bolt head and nut.

SKILLING – HELLE – CHRISTIANSEN – ROBERTSON

Mr. Malcolm P. Levy 2 August 29, 1968

4. Washer requirements for ASTM A490 high-tensile bolts are as follows:

   a. With holes not more than 1/8" larger than the nominal bolt diameter, standard hardened washers are required under both bolt head and nut.

   b. For all other cases, 1/2" thick plate washers are required under both bolt head and nut.

This information was given to Mr. Larry Wittig, as Professor Crandall was not expected in the laboratory for the remainder of the week.

Next, the equipment was examined and the following comment submitted to Mr. Wittig:

1. The quality of welding varies from poor to inexcusable. Every defect known to the writer and detectable by casual visual examination was found in profusion. Since stress levels are very low, the quality of welding may not adversely affect test results. Still, the writer recommended that key welds be cleaned by wire brush and examined from time to time throughout the test program.

2. The device intended to provide transverse stability is totally inadequate if stiffness in the transverse direction is required. Suitable techniques for improving the transverse stiffness were proposed, should remedies be required.

3. The basic geometry of the "trusses" is far from ideal. The writer pointed out eccentricities which should affect truss stiffness by a substantial margin. Such eccentricities, of course, will not exist in the building construction.

4. The lack of adequate stiffness in the test frame was discussed. The introduction of flange bending, the effects of stress concentration and the like, and the effects of the quality of welds (see 1. above) on the behavior of the frame were discussed in some detail.

5. Mr. Wittig pointed out that the drive bearing lacked the capability to resist side thrust and that his repeated efforts had been unsuccessful in preventing the drift of the bearing. This drift results in a sudden impact on the test rig, causing transverse oscillation and rendering the rig useless. Mr. Wittig stated that he was prepared to order a new bearing and that delivery of such bearing should be accomplished within a week.

SKILLING – HELLE – CHRISTIANSEN – ROBERTSON

Mr. Malcolm P. Levy 3 August 29, 1968

6. It was noted that bolt sizes do not always compare to the requirements shown in the Drawings. Mr. Wittig pointed out that AISC values for the lesser bolts indicate that bolt slip should not occur. The writer pointed out the statistical behavior of such bolts, the difficulty in measuring the detecting bolt slip and the necessity of preventing such slip. and

It was observed that no meaningful work had been accomplished or would be accomplished for at least a week or two. Mr. Wittig stated that he would be returning to regular classroom work at the end of the third week in September. When the writer pointed out that the test work would still be under way, Mr. Wittig indicated that he intends to continue his participation in the test program and that additional help could be obtained. It is the writer's opinion, not expressed to Mr. Wittig, that it is unlikely that any useful testing will be accomplished within the next three or four weeks.

Other than as expressed above, the writer found the equipment to be sound and of good design. Probably more important, Mr. Wittig appears to be dedicated and resourceful.

It is the writer's opinion that much of the original intent of the test program may be lost because of deficiencies in the test equipment. Specifically, the writer doubts that the assembly will adequately duplicate conditions as they will exist in the building. Still, with all of its defects, the equipment may be substantially closer to such a simulation than was accomplished by the program conducted by 3M under the supervision of SHCR.

Very truly yours,

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Leslie E. Robertson

LER:s
cc: Mr. Lester Feld, PNYA
Dr. Stephen Crandall, MIT
Mr. Larry Wittig, MIT

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Consulting Structural and Civil Engineers · 230 Park Avenue, New York, N. Y. 10017 · Mu. 9-8874

John B. Skilling · *Helge J. Helle* · *John V. Christiansen* · *Leslie E. Robertson*

Manager
Wayne A. Brewer

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Joseph F. Jackson

May 22, 1969

Port of New York Authority
World Trade Center Planning
111 Eighth Avenue
New York, New York 10011

Attention: Mr. Malcolm P. Levy

Reference: The World Trade Center
Damping Units

We have reviewed the report, "Test of Viscoelastic Damping Units for World Trade Center Tower Buildings", by S. H. Crandall and L. E. Wittig, dated April 23, 1969. This is an excellent report confirming in a general way the test results obtained by SHCR-3M. Also, this report gives additional data which are relevant to an evaluation of the performance of the damping units in the system environment of the intended installation.

From the photographs of the specimens in Figures 8 and 21, we surmise that an additional bolt hole was made at M.I.T. in the structural bar of each specimen to fit the test jig of the ultimate strength test. This additional hole overlaps the original bolt hole. The overlapping holes probably would not influence the strength so long as the forces are transmitted by friction. Should a major slip of the bolts occur, there is no doubt that the overlapping hole will affect the ultimate strength either in tension or compression. In appendix C, the ultimate strength of Specimens No. 14 and No. 16 were recorded as 49,000 lbs. and 48,000 lbs., respectively, whereas the corresponding Force-Elongation curves indicate maximum forces of 57,000 lbs. and 38,500 lbs., respectively. The reason for the discrepancy is not clear to us. In any case, the conclusions of the report are not affected by these two comments.

We would like to note that the Ultimate Strength in compression and in tension of this test series has a mean value of 47.7 kips with a standard deviation of

FRANK HOELTERHOFF
ROBERT E. LEVIEN
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CHARLES SANDUSKY
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RICHARD E. TAYLOR
E. J. WHITE, JR.

SEATTLE OFFICE: 1840 WASHINGTON BUILDING, SEATTLE, WASHINGTON 98101

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Port of New York Authority
Attention: Mr. Malcolm P. Levy - 2 - May 22, 1969

9.3 kips and that this combination of values would have failed to meet the Acceptance Requirements proposed in our letter dated May 2, 1969. The results of the compression tests conducted by 3M Company had a mean of 54.1 kips with a standard deviation of 4.5 kips and these values would meet the proposed requirement of mean Ultimate Strength = 45.0 +1.5 (S.D.) kips in compression. This comment should be considered prior to forwarding copies of this document to 3M for their use. Also, when conditions will permit, it is important that a copy be forwarded to 3M as this information cannot help but assist 3M in meeting their contractual commitments.

While we concur with most of the conclusions stated in Section IV of the report, it is clear that Messrs. Crandall and Wittig are not structural engineers, as their suggestions are not wholly practical. We wish to comment on this section as follows:

1. The program of periodic testing of random samples of the installed and of the stored unused dampers has long been in the test program for WTC and was discussed both at MIT and at Mr. Kyle's office.

2. It is neither necessary nor practical to test the local frame stiffness as proposed in this report. It is not practical because of the structural interconnection of column-to-column and of truss-to-truss through the structural ties of spandrel, bridging and slab. It is not necessary as the column stiffness plays only a minor role in the system and because the truss stiffness can be calculated with considerable accuracy. Previous calculations for uniformly loaded trusses have been verified through load testing of actual trusses. In short, the only way to perform this test requires that many trusses be loaded simultaneously (as would occur in the real building) or else a structural separation must be provided around a single truss by cutting both the slab and the bridging - this latter technique should not be considered. We do not feel that the cost of this proposed test is warranted.

3. Additional tests are cited which would be of interest to the profession. In this regard, we have two thoughts:
   a) SHCR is preparing a paper to be delivered before the ASCE, or similar organization, discussing the use of such dampers in building construction and presenting a method of analysis for such dampers. The paper will, of course, be presented to PNYA for its review in the light of any impact it may have on the rentability or other facet of The World Trade Center.
   b) SHCR, with PNYA concurrence, has contacted AISC with the view of obtaining technical and/or financial assistance in the performance of post-construction testing. SHCR will, of course, pursue this question further with AISC in the months ahead.

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Port of New York Authority
Attention: Mr. Malcolm P. Levy -3- May 22, 1969

We note that our copy of this report does not include Appendix E. We assume that other omissions, if any, have no bearing on the conclusions of the report.

We will report to you further as our proposals for additional testing become solidified. In the interim, should you have further questions, do not hesitate to call.

Very truly yours,

SKILLING, HELLE, CHRISTAINSEN, ROBERTSON

Leslie E. Robertson

cc: Messrs. L. S. Feld, PNYA
J. M. Kyle, PNYA
S. H. Crandall, MIT
L. E. Wittig, MIT

LER/ld

STEPHEN H. CRANDALL
PROFESSOR OF MECHANICAL ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE MASSACHUSETTS

June 2, 1969

Mr. John M. Kyle, Chief Engineer
The Port of New York Authority
111 Eighth Avenue at 15th Street
New York, New York 10011

Dear Mr. Kyle:

This letter is written in response to the letter from Mr. L. E. Robertson of SHCR dated May 22, 1969, and addressed to Mr. M. P. Levy. In his letter Mr. Robertson raises some questions in connection with our report "Test of Viscoelastic Damping Units for World Trade Center Tower Buildings" by Crandall and Wittig, April 23, 1969. I shall try to answer these questions.

With regard to the ultimate tests the explanation in the report is somewhat abbreviated. Let me give some further details here. The testing machine we used had a large dial which indicated the force applied to the specimen by a hydraulic drive. For static and slow-speed testing this force is read off point by point by the operator. Since our rate of loading was fairly rapid we made no attempt to obtain the force history from the dial. We did, however, record the maximum reading of this dial for each test (this was facilitated by having the pointer drive a marker which remained at the highest level). In order to record the force history we used strain gages on the test fixture. The gages for the compression test are visible in Fig. 8 of the report. For the tension tests the test fixture made use of the normal bolt holes of the element and was long enough to provide adequate length for the gage section. In the tension tests there was good agreement (within one or two kips) between the ultimate load registered on the dial of the testing machine and the peak of the force-displacement curve based on the strain gage signals. In the case of the compression tests we had to compromise on the length of the test fixture. Too long a fixture would encourage buckling of the element and too short a fixture would compromise the strain gage test section. In order to gain a little length we moved the bolts a little closer by drilling an extra hole in the element as shown in Fig. 21. Note that there is full bearing for the bolts for compressive loads. In the case of the compression tests there was more discrepancy between the

-2-

ultimate load registered on the dial of the testing machine (this value is noted at the bottom of figures such as Fig. 17) and the peak of the force-displacement curve. The greatest discrepancies (specimens 14 and 16) occurred where compressive failure was accompanied by large amounts of buckling. The sense of the discrepancy was opposite in these two cases.

Our interpretation of this discrepancy is that because of the short gage length our strain gages (which were calibrated for perfectly axial loading) are no longer correct when a large bending moment is superposed. We, therefore, considered the machine dial reading to provide the best estimate of the ultimate load in these cases. The values given by the machine dial reading were used in constructing Fig. 19 and in calculating the mean and standard deviation.

We are in agreement with Mr. Robertson regarding most of his comments with the one exception concerning the necessity and practicality of testing the local frame stiffness. We would like to repeat our recommendation that the local frame stiffness be checked as soon as possible. The effectiveness of the entire damping operation could be jeopardized by inadequate local frame stiffness. Furthermore, it will be difficult if not impossible to assess the performance of the system when it is in operation if the magnitude of the local stiffness remains unknown.

We think that Mr. Robertson has overestimated the difficulties involved in making this measurement. We had been thinking in terms of one evening's work. This was under the assumption that the major contribution to the local stiffness was truly local. Mr. Robertson points out that there may be considerable diffusion of load from truss to truss. This means that instead of measuring only one load and one deflection it will be necessary to measure one load and a number (possibly 6 to 12) of deflections. This is still an entirely reasonable proposition in terms of time and money.

In more detail what we are proposing is that as soon as a tower has risen to the point where a floor which is to have dampers installed (and for which the design local stiffness has been computed) is structurally complete the test would be performed by installing an instrumented turn-buckle in the damper location of one of the central trusses. The deflection measured by an LVDT across this unit would be recorded as the tensile force was raised from zero up to 30 kips, say. The load would then be removed and the LVDT moved to the adjacent element location. Again the load would be put on and the deflection recorded to obtain the corresponding influence coefficient. The procedure would then be repeated.

-3-

The LVDT would be moved from station to station until the influence coefficient was no longer measurable. Using superposition and this set of influence coefficients it is a simple matter to predict the deflection of the entire truss-system when loaded uniformly at all the stations. If time is available it would be desirable to repeat the entire measurement at other "typical" locations (e.g., on the same floor but on other faces of the building). Ideally this test should be performed when construction is not going on (e.g., night shift, holiday) so as to minimize background noise.

I trust that these comments will be helpful to you.

Sincerely yours,

Stephen H. Crandall
Professor of
Mechanical Engineering

SHC:mr

cc: Mr. Yontar

TABLE OF CONTENTS

THE WORLD TRADE CENTER
Report No. DU-3
VISCOELASTIC DAMPING UNITS

Introduction

The importance of the action of wind on tall buildings has been generally recognized for many years. This action was traditionally conceived and treated as static forces by the community of building designers. However, measurements on existing buildings by various investigators have shown that the responses of tall buildings to strong wind are predominantly dynamic. More recently, the static and dynamic responses of the twin towers of The World Trade Center were studied by means of static and aeroelastic models in a micro-meteorological wind tunnel [1]. The experiments showed that, for the wind directions critical for the structural design, the deflections, and hence the stresses, are primarily caused by dynamic oscillation of the building. It has been established that the amplitudes of the oscillation are inversely proportional to the square root of the critical damping ratio for lightly damped buildings in turbulent wind.

The critical damping ratios intrinsic in buildings were measured by several researchers. A table of the data found in the literature is included in Appendix 1. Based on the reported data, it was estimated that the intrinsic critical damping ratio of The World Trade Center towers is [redacted] for design against excessive stresses. In order to increase the mechanical damping of the towers, viscoelastic damping units were developed for installation in the floor system. These damping units have been described previously in Report DU-1 [2]. The viscoelastic damping units are expected to increase the building damping from [redacted] to [redacted] which was assumed in the structural design of the towers. The contribution of the damping units to building damping was calculated in Report DU-1 and is further summarized in Appendix 2. The expected number of cycles of oscillation per year is also given in Appendix 2 for the damping units having amplitudes of deformation exceeding given amounts.

Testing Programs

Two testing programs have been carried out for the prototypes of the viscoelastic damping units. In Program I, twenty-two prototypes of the damping units were tested by Minnesota Mining and Manufacturing Company (3M Company) in May 1967 [2]. In Program II, thirty-nine prototypes were tested at M.I.T. by Dr. S. H. Crandall and Mr. L. E. Wittig in 1969 [3]. Whereas the prototypes in Program I are subjected to cyclical axial deformation in the form of a sine function at 0.1 Hz with constant amplitude of 0.020 inch, Program II attempts to simulate the system environment of the intended installation which consists of the exterior column, the viscoelastic damping unit, and the floor truss system.

The testing conditions of the two programs are compared in Table 1. The results of the standard tests are compared in Table 2.

Evaluation of the Prototypes

The specimens in Test Program I have dynamic stiffnesses which have a higher mean value and a higher coefficient of variation than those in Test

June 2, 1969 Page 3

TABLE I

COMPARISON OF TWO TESTING PROGRAMS

	PROGRAM I	PROGRAM II
1. Number of specimens	22	39
2. Displacement - time function	Sinusoidal	Sinusoidal
3. Displacement amplitude	0.020" constant amplitude measured across viscoelastic slab.	Variable, measured across damper seat and damper extension. Constant equivalent amplitude of 0.010", 0.019", or 0.023", if damper is replaced by an elastic rod of axial stiffness equal to 600 kips inch.
4. Rotational motion	No	Yes. Caused by vertical motion of one end of test frame.
5. Standard test	100 cycles at 0.1 Hz and at 0.020" amplitude, then an extra cycle when temperature of viscoelastic slab returns to the room temperature.	100 cycles at 0.1 Hz and at equiv. amplitude of 0.019", two extra cycles after a rest of 20 minutes. Room temperature at 75±3°F.
6. Endurance test	1000 cycles at 0.020" amplitude.	10,000 cycles at equiv. amplitude of 0.010"; 2,600 cycles at equiv. amplitude of 0.019"
7. Frequency of cycling	0.1 Hz	0.1 Hz, 0.25 Hz, 0.50 Hz
8. Mean displacement	None	Zero for standard tests. Special tests at mean displacements of +0.011", -0.0125", +0.023", and -0.021".
9. Room temperature	75 ± 5°F with 18 tests at 75 ± 3°F.	75 ± 3°F. One special test at 85°F.
10. Frame stiffness	Not applicable.	192 kips/inch (computed stiffness at 47th Floor is 600 kips/inch).
11. Rate of loading for Ultimate Strength Test	Not reported. All bolts in double shear.	0.50 inch/minute (approx.) Bolted connections same as in design for field installation.

June 2, 1969 Page 4

TABLE 2

COMPARISON OF RESULTS OF TWO TESTING PROGRAMS

STANDARD TESTS	PROGRAM I	PROGRAM II		
1. Dynamic Stiffness (kip/inch)				
Mean	825	555		
Standard deviation	122	62		
Coefficient of variation	0.15	0.11		
2. Loss Tangent				
Mean	1.38	0.84		
Standard deviation	0.18	0.17		
Coefficient of variation	0.13	0.20		
3. Ultimate Strength (kips)	Compression	Compression	Tension	All
Mean	55.0	45.0	50.4	47.7
Standard deviation	3.1	4.9	10.6	9.3
Coefficient of variation	0.06	0.11	0.21	0.1

Program II. The differences can be attributed to the greater scatter of test temperatures, to the slightly lower mean value of the test temperatures (73.7°F) and to the use of several different formulations of the viscoelastic material in Test Program I. The damping units of Program II have a mean dynamic stiffness of 555 kips per inch at 75°F, which is very close to the optimun value of [redacted] kips per inch. At the same time the coefficient of variation equal to 0.11 is very satisfactory.

The specimens in Test Program I have a mean loss tangent of 1.38 which is much better than the design minimum mean of 0.70. Futhermore, the specimens are quite uniform in the loss tangent with a coefficient of variation equal to 0.13. The specimens in Test Program II have a mean loss tangent of 0.84 with a coefficient of variation of 0.20. This is satisfactory, since the mean loss tangent of the universe represented by these specimens would be greater than 0.77 with a probability of 0.95 according to the t-Distribution.

The ultimate strength obtained in Test Program I has a mean of 55.0 kips and a coefficient of variation of 0.06, which indicated high strength and good uniformity. If the dynamic stiffness of the damping unit, K_d, remains below the design value of [redacted] kips per inch, the maximum design force in the damping unit, F_d would not exceed 34 kips (Appendix 3). If K_d reaches 900 kips per inch, maximum F_d would reach 40.9 kips. In such a case, about 20% of the damping units represented by Test Program II would be near or over the breaking point. The reasons for this discrepancy of ultimate strength between the two test programs are not clear. Perhaps, the difference in the test jigs is the source of the discrepancy. Fortunately, the results of Test Program II indicate some positive correlation between

June 2, 1969 Page 6

dynamic stiffness and ultimate strength. In fact, the coefficient of correlation between these two parameters is +0.42. This means that the damping units which have low ultimate strength tend to have low dynamic stiffness also. Since maximum force in the damping unit decreases with decreasing dynamic stiffness, the probability of breakage of the damping units under the maximum design wind condition is small if the results of Test Program II are representative of the production units. [redacted]

The special tests of Program II indicate that the damping units are satisfactory with respect to fatigue, to higher frequencies of oscillation and to a temperature rise of 10°F above 75°F.

Conclusions

The two test programs of the prototypes indicate that the damping units in the floor system will provide an expected increase of [redacted] in the critical damping ratio of The World Trade Center towers. [redacted]

June 2, 1969 Page 7

References

1. The World Trade Center Wind Report, Final Chapter, July, 1966, by Worthington, Skilling, Helle, & Jackson, Consulting Engineers, New York, N. Y. (now Skilling, Helle, Christiansen, Robertson).

2. Viscoelastic Damping Units, Report No. DU-1, The World Trade Center, July 17, 1967, by Skilling, Helle, Christiansen, Robertson, Consulting Engineers, New York, N. Y.

3. Test of Viscoelastic Damping Units for World Trade Center Tower Buildings, April 23, 1969, a report to The Port of New York Authority by S. H. Crandall and L. E. Wittig.

THE PORT OF NEW YORK AUTHORITY

World Trade Department

November 5, 1971

Minnesota Mining & Manufacturing Corp.
3M Center
St. Paul, Minnesota 55101

Attention: Mr. Don Caldwell

Re: THE WORLD TRADE CENTER - CONTRACT WTC-224.00 - TESTING OF 12 DAMPING UNITS REMOVED FROM FLOORS 26, 27, 29 & 30 - TOWER A

Gentlemen:

This will confirm oral information given to you by our Mr. Feld on 11/4/71:

3M is to perform an equivalent Acceptance Test series on the subject group of units (see Schedule X1 attached). These units were all installed in November of 1970 and remained in place for the past year in unheated space throughout a "cold" winter. We are attempting to ascertain if the units have actually been affected by the "cold" and are in fact capable of passing an equivalent acceptance test. The number and sequence of testing for loss factor and stiffness, fatigue loss and ultimate strength are to be determined by 3M.

We would appreciate your expediting this series of tests upon receipt of the units. All work is to be performed under the unit price provisions for testing under the subject Contract. Please advise this office as to your testing schedule.

Sincerely,

Malcolm P. Levy

cc: Messrs. W. Borland, D. Brown, P. Chen(SHCR), I. Feld, R. Monti, J. White(SHCR), F. Wernecke - all w/att.

Laclede Steel Company

General Offices Laclede Building
St. Louis, Missouri 63101

CONTRACT WTC-221.00
WORLD TRADE CENTER
THE PORT OF NEW YORK AUTHORITY
LACLEDE CONTRACT 67-J-31801

Mr. W. C. Borland
Coordinator of Construction
The World Trade Center
The Port of New York Authority
111 Eighth Avenue
New York, New York 10011

DATE April 3, 1969

TRANSMITTAL LETTER NO. 10

TRANSMITTAL OF FLEXURAL TESTS

Transmitted herewith is one copy each of the sequentially numbered flexural test reports listed below. Submission is in accordance with the sixth paragraph of Paragraph 105.102 "Resistance Welding" of our Contract WTC-221.00.

Flexural Test No.	Date of Test
23	12/17/68
24	12/17/68
25	12/17/68
26	12/19/68
27	12/19/68
28	12/31/68
29	12/31/68
30	1/ 7/69
31	1/ 7/69
32	1/ 7/69
33	1/24/69
34	1/24/69
35	1/24/69

For David B. Nepton
Robert D. Bay
Director of Technical Services

CC: ✓ Mr. James White
Skilling-Helle-Christiansen-Robertson
230 Park Avenue
New York, New York 10017

Mr. Al Guttentag, Project Engineer
Tishman Realty & Construction Co., Inc.
30 Church Street - 11th Floor
New York, New York 10007
(COPY NOT SENT)

May 15, 1969

R. D. BAY

RE: WTC-221.00
FLEXURAL TESTS
SHIPMENT NO. 2

The results of all Flexural Tests performed for Shipment No. 2 are shown on the attached sheet 1 of 2 dated May 15, 1969. This sheet shows the comparative deflections for incremental loads of 500 lbs. for each truss tested. Sheet 2 of 2 gives the backup data for Sheet 1.

David B. Neptune

1p

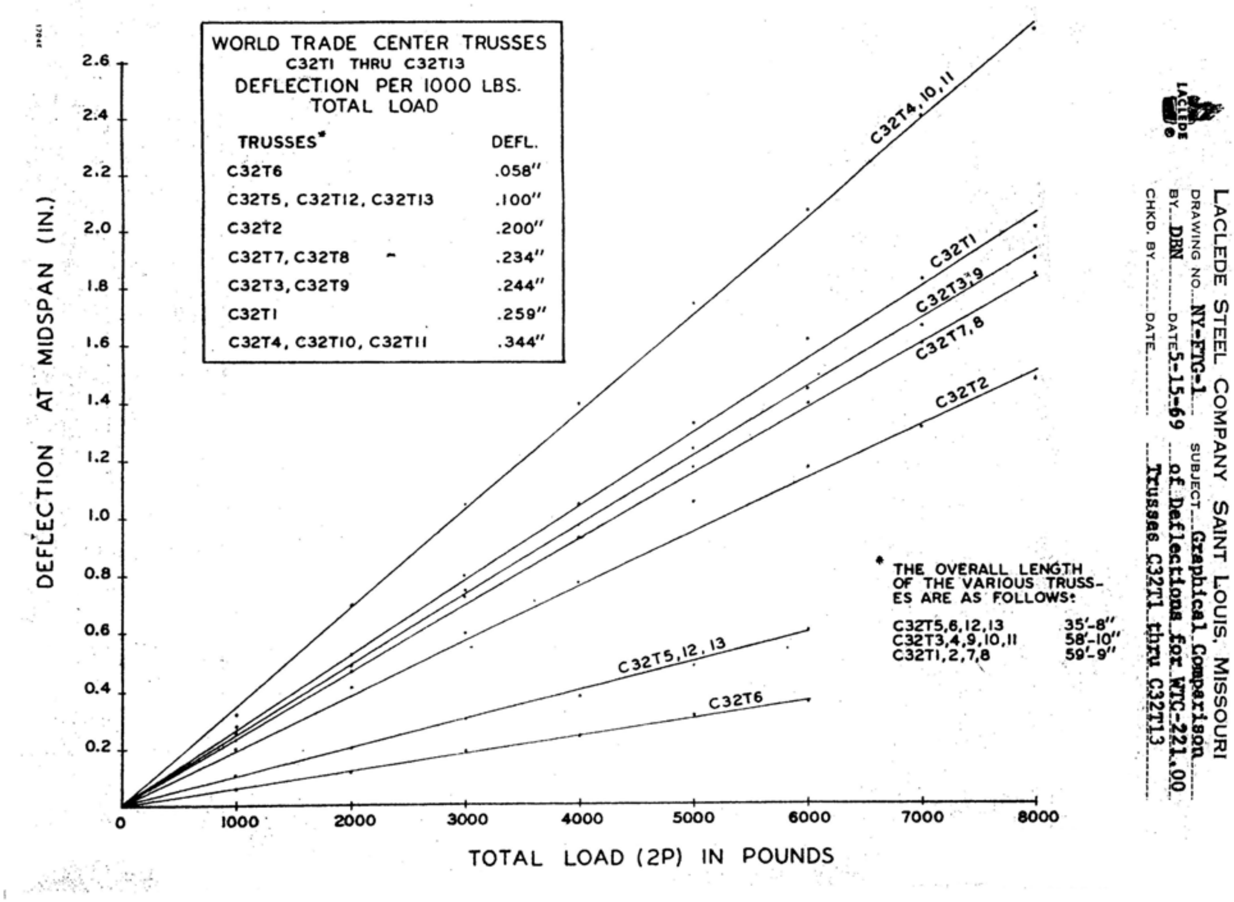
WORLD TRADE CENTER
FLEXURAL TESTS
NOS. 23 THRU 40

May 15, 1969
Page 1 of 2

Comparative Deflections+ in Inches for
Incremental Target Loads of 500 Pounds

(1) TRUSS MARK NO.	(2) TEST NO.	(3) DESIGN DEFL In.	(4) DESIGN LOAD Psf	TARGET LOAD IN POUNDS (5) 500	1000	1500	2000	2500	3000	3500	4000	4500	5000
C32T1A	24	2.000	58	.246	.551	.802	1.060	1.335	1.605	1.910	2.170	2.447	2.751
C32T2A	23	2.063	62	.207	.408	.595	.775	.997	1.165	1.335	1.535	1.752	1.962
C32T3	27	2.063	62	.262	.490	.715	.995	1.178	1.414	1.646	1.888	2.120	2.367
C32T4	29	0.750	62	.370	.708	1.029	1.357	1.683	2.033	2.372	2.743	-	-
C32T5	33	0.375	54	.104	.201	.299	.395	.500	.602	-	-	-	-
C32T6	35	0.938	62	.064	.118	.171	.226	.279	.334	.390	.446	-	-
C32T7A	25	2.063	62	.281	.510	.747	.977	1.227	1.440	1.675	1.920	2.174	2.437
C32T8A	26	2.000	62	.286	.541	.807	1.083	1.321	1.575	1.839	2.122	2.400	2.700
C32T9	28	1.938	62	.261	.501	.742	.983	1.233	1.462	1.700	1.943	2.208	2.445
C32T10	30	1.688	62	.360	.711	1.042	1.371	1.699	2.023	2.377	2.729	-	-
C32T11	31	1.313	62	.400	.742	1.070	1.414	1.756	2.095	2.437	2.793	-	-
C32T12	32	0.250	62	.113	.204	.293	.385	.478	.570	-	-	-	-
C32T13	34	0.438	62	.109	.199	.289	.378	.467	.554	-	-	-	-
C32T14AL	38	2.000	58	.281	.565	.841	1.103	1.377	1.649	1.921	2.226	2.490	2.812
C32T16AL	39	2.063	62	.273	.511	.738	.977	1.214	1.465	1.716	1.987	2.241	2.519
C32T21L	40	1.375	62	.416	.765	1.117	1.464	1.825	2.165	2.575	2.917	-	-
C32T23L	36	0.375	54	.116	.224	.326	.430	.533	.638	-	-	-	-
C32T26L	37	0.875	62	.072	.134	.195	.258	.322	.387	.449	.513	-	-

+Values represent maximum deflection at midspan


WORLD TRADE CENTER TRUSSES
C32T1 THRU C32T13
DEFLECTION PER 1000 LBS. TOTAL LOAD
TRUSSES* DEFL.
C32T6 .058"
C32T5, C32T12, C32T13 .100"
C32T2 .200"
C32T7, C32T8 .234"
C32T3, C32T9 .244"
C32T1 .259"
C32T4, C32T10, C32T11 .344"
DEFLECTION AT MIDSPAN (IN.)
TOTAL LOAD (2P) IN POUNDS
C32T4,10,11
C32T1
C32T3,9
C32T7,8
C32T2
C32T5,12,13
C32T6
* THE OVERALL LENGTH OF THE VARIOUS TRUSSES ARE AS FOLLOWS:
C32T5,6,12,13 35'-8"
C32T3,4,9,10,11 58'-10"
C32T1,2,7,8 59'-9"
LACLEDE STEEL COMPANY SAINT LOUIS, MISSOURI
DRAWING NO. NY-FTG-1
SUBJECT Graphical Comparison of Deflections for WTC-221.00 Trusses C32T1 thru C32T13
BY DBN DATE 5-15-69
CHKD. BY DATE

NOTES

(1) There are three different lengths of trusses tested. These three lengths are shown below along with the mark numbers of the trusses which have that particular length.

59'9"	58'11"	35'8"
C32T1A	C32T3	C32T5
C32T2A	C32T4	C32T6
C32T7A	C32T9	C32T12
C32T8A	C32T10	C32T13
C32T14AL	C32T11	C32T23L
C32T16AL	C32T21L	C32T26L

(2) Refer to this test number to obtain more information about the truss and the test results.

(3) Refer to S.H.C.R. drawing number 7-AB1-54 dated 2-15-68 and revised 11-25-68 which gives the camber at midspan for each type of 32" truss.

(4) Refer to Laclede Contract WTC-221.00 (October, 1967) pages TF1-2, 3, 4 and 21. Design loads were not given for trusses C32T14AL, 16AL, 21L, 23L and 26L. Their design loads were obtained from Gene Chorny of S.H.C.R.

(5) Two equal, concentrated loads were applied to each truss. Each load was applied at a panel point. The target load shown in the Table on page one is the magnitude of each applied concentrated load; the total load on the truss would be double this value. This target load is not the actual load at which the deflection listed below it occurs because the load cell reading in pounds does not equal the load applied to the truss by each hydraulic jack. The target load is very close to the actual load and is used for clarity in the table. The corresponding actual load for each target load is as follows:

Target Load	Actual Load
500	499.8
1000	999.6
1500	1499.8
2000	1999.2
2500	2499.0
3000	2998.8
3500	3498.6
4000	3998.4
4500	4498.2
5000	4998.0

For information on testing procedures, equipment used and positioning of loads for each truss, refer to Flexural Test Sheets Nos. 23 thru 40.

CC: R. D. Bay
J. R. Paul

September 7, 1967

A. C. WEBER

WORLD TRADE CENTER
SHEAR KNUCKLE TEST

Enclosed are Sheets 1 and 2 dated September 7, 1967.

Sheet 1 of 2 gives the results of transverse loading of shear knuckles. Lightweight concrete similar to the type to be used on the World Trade Center was used in this test. Specimen #2 (compressive strength of 2600 psi at 27 days) failed at 30,100#. Support brackets were not used on this test and rotation of the slabs obviously lowered the ultimate capacity. Specimen #1 had a 6 day compressive strength of 1330# and a total shear capacity of 37,070#. The side slabs were restrained from rotation on Specimen #1. The average shear transfer per knuckle for the two tests was 16,800#.

Sheet 2 of 2 gives the results of longitudinal loading of shear knuckles. Standard concrete (average strength of 3800 psi) was used in this test. The average maximum load resisted by five specimens was 55,230# or 27,615#/shear knuckle.

J. R. Paul

sak

Laclede Steel Company

General Offices, Arcade Building

St. Louis, Missouri 63101 August 10, 1967

Mr. Wayne Brewer
Skilling, Helle, Christiansen
and Robertson
230 Park Avenue
New York, New York 10017

Dear Wayne:

Shear Connectors
<u>World Trade Center Floor Trusses</u>

We are sorry that you could not get to St. Louis last Tuesday to witness some of the testing on the shear members and the application of the fireproofing to the painted open web trusses.

I presume Jim White has told you about the application of the insulating material on the joists which apparently worked very well.

In our conversation with the plastering contractor who handled the test application and the representatives of the Zonolite Division of the W. R. Grace Company, it seems that the loss because of the round webs was far less than they anticipated and total loss of material with the system as they applied it would be under 15%. This application involves less material than a solid section of the same dimensions and is no different from angle or structural section trusses attempted previously.

For your information, on the shear member testing we have averaged the bearing values for the shear members with 2,850 psi concrete and find that a 28,810# average value has been obtained with some running as high as 33,000#. This is well over the 17 kips we discussed and since the bearing of the shear members is solely a function of the concrete compressive strength, the 3,000# material you have specified for the World Trade Center towers should find excellent transference of top chord compression stresses to the floor slab. On one of the tests witnessed by Jim White of a six-day concrete with a strength of only 1,330 psi

.DE STEEL COMPANY

Mr. Wayne Brewer
Skilling, Helle, Christiansen
and Robertson

Page 2

August 10, 1967

the loading across or normal to the shear members developed a 18,500# average value for shear connector bearing.

One of these specimens is being retained to 28 day strength although we are not too sure that the very lightweight mix will be developing much more than 1,800# to 2,000# in the concrete.

Dr. Galambos at Washington University who has been performing the Steel Joist Institute composite joist and truss tests, has told us, and I believe confirmed this to Jim White, that approximately the same shear value for the Laclede extended web connectors could be expected in all directions when the shear connector is attached in a normal concrete top slab. This means with the 3,000# concrete we could expect a 28 kips transference value across, as well as in line with the extended web panel point shear member.

As an aside, I believe Dr. Galambos told Jim White that in his tests he has had no measurable stress in the steel top chords of Laclede joists and trusses indicating that the shear members have been sufficiently good to take all the compression in the concrete top slab of the composite design.

We hope to be hearing from you shortly regarding sizing of members and the design of transverse trusses in the tower corners where it seems likely that shear members may be limited as you had planned it, to the primary floor trusses with transverse trusses furnished without extended web panel points.

Yours very truly,

LACLEDE STEEL COMPANY

A. Carl Weber
Vice President

ACW:pjz

cc: Mr. Jim White
Skilling, Helle, Christiansen and Robertson

Mr. Lester Feld
Port of New York Authority

SKILLING – HELLE – CHRISTIANSEN – ROBERTSON

Consulting Structural and Civil Engineers · 230 Park Avenue, New York, N. Y. 10017 · Mu. 9-8874

John B. Skilling · Helge J. Helle · John. V. Christiansen · Leslie E. Robertson

Consultants
Harold L. Worthington
Joseph F. Jackson

April 19, 1968

Mr. R. M. Monti
Port of New York Authority
Office of the Construction
Manager – Room 1119
30 Church Street
New York, New York 10007

Reference: The World Trade Center
Contract WTC-221.00, Laclede
Load Tests

Dear Ray:

Attached are load test sketches 1BV and 1BH dated 4/16/68, prepared by Laclede Steel Company.

The test pieces and procedures indicated on these sketches are acceptable for use in tests to establish the strength of the 24T to C32T truss connections, subject to the following additional requirements:

Sketch 1BV

1. C32T top chords 7"± apart.

2. Tests be conducted with weld X of 1/4"x3", 5/16"x3" and 3/8"x3".

3. Two sets of tests to be conducted –

   a. with "knuckle" restrained as shown on 1BV. (SHCR feels that a load cell can be substituted for the restraint shown, if practical.)

   b. without "knuckle" restrained. This will allow evaluation of the joint strength for the construction loading conditions.

WAYNE A. BREWER
P. S. A. FOSTER
FRANK HOELTERHOFF
ROBERT E. LEVIEN
V. A. PRISADSKY
KENT R. ROGERS
CHARLES SANDUSKY
WILLIAM D. WARD
E. J. WHITE, JR.
LORENTS L. WIDING

SEATTLE OFFICE: 1840 WASHINGTON BUILDING, SEATTLE, WASHINGTON 98101

WTCI-87-I

SKILLING – HELLE – CHRISTIANSEN – ROBERTSON

Mr. R. M. Monti

April 19, 1968

Sketch 1BH

1. Tests to be conducted with weld X of 1/4"x3", 5/16"x3" and 3/8"x3".

2. Load to be applied 1/2" from top of angle (center of gravity).

3. Support of C32T web members close to top chord, as shown on 1BH, will require test results to be adjusted for the flexibility of these web members. We understand that this support location is limited by the test machine size. This location of the support will, however, allow an evaluation of the lateral bending of the vertical leg of C32T top chord angle, and is therefore acceptable.

Except for weld X sizes to be tested, these additional requirements were discussed with Carl Weber by telephone on 4/18/68. Information in boxes on 1BV and 1BH was added by SHCR.

Very truly yours,

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Wayne A. Brewer

WAB:s
cc: Messrs. A. C. Weber, B. Bay, Laclede
Mr. L. S. Feld, PNYA
Mr. A. J. Guttentag, TRCC

Enclosure

CC: T. M. Chura
D. B. Neptune
File Copy

March 18., 1969

R. D. BAY

RE: TESTS FOR BEARING CAPACITY
OF WORLD TRADE CENTER TRUSSES

The attached sheets summarize the tests conducted Friday, March 7 at the Madison plant. These tests are broken down into two groups. Group No. 1 consists of seven (7) tests on various bearing ends of scrapped trusses to determine the bearing capacity of our World Trade Center trusses. The results of these tests are on page one while a general sketch of how the bearing end was tested is shown on page three (Figure 1). The following is a summary of the test results:

1. Only one test resulted in a broken weld and this was at a load 18K greater than the load which caused the initial bending of the angles.

2. Using a 2" plate instead of a 4" plate for the bearing surface results in a more critical loading condition and an earlier angle deformation.

3. The core end withstands a greater load before failure than the column end. This can probably be attributed to a smaller L/R ratio and a more compact section.

4. Arc welding the bottom of the vertical VI strut decreases the possibility of a weld failure. The failure which occurs is then a failure of the bearing angle which begins to deform noticeably at approximately 30K.

Group No. 2 consists of four (4) tests on bearing ends having only arc welding joining the web and angles together; i.e., no resistance welding was used. The purpose of these tests was to determine the strength of repaired bearing ends that would be welded onto our trusses at the jobsite. Two types of tests were performed. The first type of test shown in Figure 2-A, page 4 tested the capacity of the end as a unit. The second type of test shown in Figure 2-B, page 4 tested the strength of each joint in the bearing end. The results of these tests seem to indicate that those bearing ends arc welded to the trusses at the jobsite will be strong enough to support the required load if the welding is performed by a qualified welder under good supervision.

David B. Neptune

ds

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

Consulting Structural and Civil Engineers · 230 Park Avenue, New York, N. Y. 10017 · Mu. 9-8874

John B. Skilling · Helge J. Helle · John V. Christiansen · Leslie E. Robertson

Manager
Wayne A. Brewer

Consultants
Harold L. Worthington
Joseph F. Jackson

November 3, 1969
File: WTC-235C

Mr. Lester S. Feld
Port of New York Authority
World Trade Center Planning
111 Eighth Avenue
New York, New York 10011

Reference: The World Trade Center
Contract WTC-235.00, Bethlehem Fabricators
Stud Shear Connector Capacity with Rollform Type "B" Steel Deck

Dear Lester:

At your request, we are forwarding to your attention the following information regarding a test program to establish the capacity of 3/4 inch diameter by 4½ inch long stud shear connectors when welded through the valleys of Rollform Type "B" steel deck.

Two 15 foot long test beams conforming to Attachment #1 are required. During the testing operation, the load-deflection and load-slip behavior for each beam should be determined using three (3) 0.001 dial gages and eight (8) SR-4 type A-1 strain gages in accord with Attachment #3.

Load should be applied in 4 kip increments and readings at all gages should be recorded before the next increment of load is applied.

Six 4'-3" long pushout specimens are required in accord with Attachment #2, four (4) with steel deck and two (2) with solid slabs. The load-slip behavior of each specimen should be determined by using two (2) 0.001 inch dial gages, one for each pushout slab. Dial gages should be mounted as shown in Attachment #2, and readings should be recorded for each 4 kip increment of loading.

Lightweight concrete required for the test specimens and test cylinders will amount to approximately 85 cubic feet. We recommend use of Nytralite lightweight aggregate, Master Builders Pozzolith 100R and MBVR, and Type III (high-early) cement of the brand on hand at the local ready mix concrete source chosen to supply the 110 pound (air dry weight) f'c = 3000 psi concrete for the test specimens.

ROBERT E. LEVIEN
PAUL S. A. FOSTER
FRANK HOELTERHOFF
KENT R. ROGERS
CHARLES A. SANDUSKY
WILLIAM D. WARD
E. J. WHITE, JR.
LORENTS L. WIDING

RICHARD CHAUNER
ERNEST T. LIU
JOSTEIN NESS
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HAROLD D. ROEY
RICHARD E. TAYLOR

SEATTLE OFFICE: 1940 WASHINGTON BUILDING, SEATTLE, WASHINGTON 98101

SKILLING – HELLE – CHRISTIANSEN – ROBERTSON

Port of New York Authority
Attention: Mr. Lester Feld -2- November 3, 1969

The recommended concrete mix is as follows:

Cement (Type III)	540 #
Sand*	1275 #
Lightweight Aggregate** (3/4" to #4)	900 #
Admixture	Pozzolith 100R 24 oz. MBVR 3 to 5 oz.
Water	36 gallons
Air Content	6 per cent

* Natural sand, fineness modulus 2.40 to 2.70, specific gravity of 2.65 assumed.
** Nytralite aggregate, specific gravity of 1.45 assumed.

Based on the above, a minimum of 3000 pounds of Nytralite aggregate will be required. Barring unforeseen events, Nytralite could provide aggregate at the test location upon three (3) days notice. Pozzolith 100R and MBVR are available upon a notice of one or two days.

Regarding concrete test cylinders, the following number of cylinders should be provided for each batch of concrete used to fabricate pushout and beam test specimens:

4 – 6 x 12 cylinders – test at three (3) days
4 – 6 x 12 cylinders – test at seven (7) days
4 – 6 x 12 cylinders – test on day of pushout tests
4 – 6 x 12 cylinders – tensile splitting tests per ASTM-A496

2 – 6 x 12 cylinders-air dry weight-cure seven (7) days moist, then dry 21 days at 73.4±2 degrees fahrenheit, 50 ± 2 percent humidity.

Regarding mechanical properties of the 12WF 27 test beam members, two tensile coupons should be taken from the bottom flange of each test beam centered from the web and centered on the quarter span point. Two tensile coupons should be taken from the web of each test beam at mid-height of the web, with one coupon centered on the quarter point of each beam. The test coupons should conform to ASTM A307, Figure 4, and should be longitudinal specimens.

Mechanical properties of four (4) 3/4 inch diameter by 4 1/2 inch long stud shear connectors should be determined in accord with AWS D1.0-69, Section 430.

The remaining specifics regarding fabrication and testing of materials and stud shear connector test specimens can be finalized at meetings with the Bethlehem Fabricators and the personnel at the testing facility.

Very truly yours,

SKILLING, HELLE, CHRISTIANSEN, ROBERTSON

James White

James White
JW:ans

THE PORT OF NEW YORK AUTHORITY
111 Eighth Avenue at 15th Street, New York, N.Y. 10011

World Trade Department

Guy F. Tozzoli, Director Telephone (212) 620-8171

CONFORMED COPY

January 6, 1970

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania 18015

Attention: Professor Roger G. Slutter
Chairman, Operations Division

Re: THE WORLD TRADE CENTER - Contract WTC-721.00
Laboratory Services - Stud Shear Connector
Capacity with Roll Form Type "B" Steel Deck

Gentlemen:

I. The undersigned, The Port of New York Authority (hereinafter called the "Authority") hereby offers to retain the Fritz Engineering Laboratory (hereinafter called the "Laboratory") to perform stud shear connector capacity tests using Roll Form Type "B" steel deck for The World Trade Center being constructed by the Authority in New York City including:

A. All tests as outlined in the attached letter of November 3, 1969 from Mr. James White of Skilling, Helle, Christiansen, Robertson to our Mr. Lester S. Feld.

B. Supervision of installation of deck and studs on steel specimens.

C. Furnishing of concrete forms, reinforcing steel, Type III Cement, sand and water for all concrete slabs and specimens.

D. Casting and curing of concrete slabs and specimens.

E. Submittal of six (6) copies of the Test Report to the Authority to the attention of Mr. Malcolm P. Levy, Chief of Planning and Construction Division, The World Trade Center, Room 300, 111 Eighth Avenue, New York, New York 10011.

Fritz Engineering Laboratory - 2 - January 6, 1970

II. The Authority has arranged for the following items to be furnished by others and delivered to the Laboratory by November 19, 1969:

A. Two (2) 15 foot long test beams with steel deck and studs installed by others prior to delivery.

B. Four (4) 4'-3" long pushout specimens with steel deck and studs installed on both flanges by others prior to delivery.

C. Two (2) 4'-3" long pushout specimens with studs installed on both flanges by others prior to delivery.

D. Approximately 3000 pounds of Nytralite Lightweight Aggregate.

E. Approximately two gallons of Master Builders Pozzolith 100R and MBVR for use as admixture.

III. As full compensation for the performance of all your obligations herein, the Authority agrees to pay the Laboratory the sum of the following amounts:

(a) A unit price of $2000.00 per 15 foot beam test for each of the two beam tests required.

(b) A unit price of $400 per pushout tests for each of the six required pushout tests.

The Laboratory shall not perform any services beyond the point at which the total payments to be made hereunder exceeds $6400.00, unless expressly authorized by the Director to perform such services in a writing which expressly recognizes that said amount of $6400.00 will be exceeded. In the event said writing specifies a maximum total amount for services hereunder, this Agreement shall be deemed amended to substitute said amount for the aforesaid amount of $6400.00.

IV. Within 15 days after the receipt from the Laboratory of the Test Report, the Director will estimate and certify to the Authority the amount of compensation due to the Laboratory. The Authority will within fifteen (15) days after the date of such certification of the Director advance to the Laboratory, by check, the sum certified.

V. No certificate or payment shall at any time preclude the Port Authority from showing that such certificate or payment was incorrect or from recovering any money paid in excess of that lawfully due.

VI. The Laboratory shall not issue or permit to be issued any releases, advertisements, or literature of any kind which refer to

THE PORT OF NEW YORK AUTHORITY

Fritz Engineering Laboratory - 3 - January 6, 1970

the services performed hereunder, unless you first obtain the written approval of the Authority. Such approval may be withheld if for any reason the Director, in his sole discretion, believes that the publication of such information may be harmful to the public interest or in any way whatsoever undesirable.

VII. The Laboratory shall promptly and fully inform the Director of any patents or disputes, whether existing or potential, of which you have knowledge, relating to any idea, design, method, materials, equipment, or other matter involved in the services hereunder.

VIII. All drawings, specifications, reports, computations, records, data, charts, documents or other papers, or any type whatsoever, whether in form of writing, figures or delineations, which are prepared by the Laboratory at any time, either prior or subsequent to signature of this Agreement, by the Authority, its Commissioners, officers, agents or employees, is not given in confidence and may be used or disclosed by or on behalf of the Authority without liability of any kind.

IX. All information of any nature whatsoever which is in any way connected with the services performed in connection with this Agreement, regardless of the form of communication which has been or may be received from the Laboratory at any time, either prior or subsequent to signature of this Agreement, by the Authority, its Commissioners, officers, agents or employees, is not given in confidence and may be used or disclosed by or on behalf of the Authority without liability of any kind.

X. Under no circumstances shall the Laboratory communicate in any way with any department, board, agency, commission, or other organization whether governmental or private in connection with the services to be performed hereunder except upon prior written approval and instructions of the Director provided, however, that data from manufacturers and suppliers of materials shall be obtained by you when and as you find such data necessary, unless otherwise instructed by the Director.

XI. This Agreement being based upon your special qualifications for the services herein contemplated, any assignment or other transfer of this Agreement or of any part hereof or of any monies due or to become due hereunder without the express consent in writing of the Director shall be void and of no effect as to the Authority.

XII. The Director, at his option, may, at any time, and with or without cause, terminate this Agreement as to any services not yet rendered. The Laboratory shall have no right of termination as to services under this Agreement without just cause. Termination by either party shall be by registered letter addressed to the other at its address hereinbefore set forth. Should this Agreement be so terminated, Fritz Engineering Laboratory - 4 - January 6, 1970

the Laboratory shall receive no compensation for any services not performed, and the Laboratory shall be paid as full compensation for services performed an amount computed as above set forth.

XIII. This Agreement shall be effective as of November 14, 1969. All of the services hereunder shall be performed as expeditiously as possible. The services shall in any case be completed on or about February 1, 1970. Time is of the essence of performance of all your services under this Agreement.

Any services performed for the benefit of the Authority by the Laboratory at any time, if expressly and duly authorized by the Director, shall be deemed to be rendered under and subject to this Agreement (unless referrable to another express, written, duly executed agreement), and no rights or obligations shall arise out of such services except as may be provided for under this Agreement.

XIV. The entire Agreement between us is contained herein and no change in or modification, termination or discharge of this Agreement in any form whatsoever shall be valid or enforceable unless it is in writing and signed by the party to be charged therewith in the manner hereinbefore expressly provided shall be effective as so provided.

If the foregoing meets with your approval, please indicate your acceptance by signing the enclosed copy of this letter in the lower left-hand corner and returning it to the attention of Mr. Malcolm P. Levy, Chief, Planning and Construction Division, The World Trade Center, Room 300, 111 Eighth Avenue, New York, New York 10011.

Very truly yours,

THE PORT OF NEW YORK AUTHORITY

Guy F. Tozzoli

Guy F. Tozzoli, Director
World Trade Department

FRITZ ENGINEERING LABORATORY
LEHIGH UNIVERSITY

By R. G. Slutter

Title Director, Operations Division

Date January 21, 1970

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