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Blast Analysis of the SlenderWall® System

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Prepared For:

Smith-Midland
5119 Catlett Road / PO Box 300
Midland, VA 22728

Point of Contact/ Performing Agency:

Applied Research Associates, Inc.
119 Monument Place
Vicksburg, MS 39180
(601) 638-5401

Corporate Office:

Applied Research Associates, Inc.
4300 San Mateo Blvd., NE
Albuquerque, NM 87110

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Introduction

Since its inception in the early 1990's the SlenderWall product has been used to clad in excess of 60 commercial building. During this time only a few buildings required that SlenderWall meet a blast requirement. ARA was contracted to determine the capabilities of SlenderWall to meet blast requirements such as those contained in the Unified Facilities Criteria (used for DoD facilities) and the Interagency Security Committee (*ISC*) Security Design Criteria (used for GSA facilities).

The results of the analysis documented herein demonstrate that the SlenderWall product has the capability to resist moderate blast loads with minimal changes to the existing commercially used design. For the system analyzed, the 1/4-inch Nelson studs were the only component of the system which did not perform satisfactorily and the issue was only with rebound under the chosen blast design load. The issue can be alleviated by reducing the spacing of the studs or providing a shim between the steel stud frame and the precast concrete at each Nelson stud location. Many projects do not have a rebound requirement and failing in rebound may be an acceptable failure mode in many cases.

Description of SlenderWall

The SlenderWall cladding system combines four proven components: architectural precast concrete, hot-dipped galvanized welded wire, insulated stainless-steel anchors, and heavy gauge galvanized steel or stainless steel studs, to create a single, efficient exterior wall system for new construction and renovation.

Designing projects with SlenderWall reduces building foundation and structure costs, exterior framing costs, shipping and installation costs, field construction schedules, and thermal transfer. The system also adds "bonus" square footage on every floor due to the floor edge mounting of the panels. The design isolates the exterior precast concrete cladding from the structural stresses associated with wind loading, steel frame movement, expansion and contraction and seismic shock.

Figure 1. Building employing SlenderWall exterior cladding.

Discussion of Blast Loading

General Discussion of Blast Loads

When a high explosive is initiated, a very rapid exothermic chemical reaction occurs. As the reaction progresses, the solid or liquid explosive material is converted to very hot, dense, high-pressure gas. Because of the comparatively low density of the surrounding air, the explosion products initially expand at very high velocities in an attempt to reach equilibrium with the surrounding air. This expansion creates a shock wave that is often referred to as the blast wave or shock front.

As the explosive products expand, the pressure at the interface separating them from the air drops rapidly. An explosive detonation can be visualized as a bubble of highly compressed, hot air that expands until it reaches equilibrium with its surroundings. As a shock front propagates away from the detonation point, its peak pressure decreases rapidly because of geometric divergence and because of dissipation of energy in heating the air. As the shock front pressure decreases, the propagation rate, particle velocity, density and temperature of air behind the front also decrease. The duration of the wave, however, increases as it expands outward. The magnitude and distribution of the shock wave pressures depend on the explosive properties, casing effects if the explosive charge is encased, the distance from the target, and the reflection of the pressure wave from the ground, the target, and surrounding structures.

When an explosive is detonated near the ground surface, the resulting shock wave expands as a hemisphere, moving up and out from the source. In open air, the shock wave's peak pressure is called the incident pressure. This pressure is actually an overpressure as it is the pressure in excess of the existing ambient atmospheric pressure. When the incident pressure impinges upon a structure, it reflects, producing what is known as a reflected pressure which may be several times greater that the incident pressure.

Blast Loads Considered in the Analysis

In an effort to minimize the likelihood of mass casualties from terrorist attacks, two similar, yet distinct, sets of criteria have been established by two major bodies in the federal government tasked with guiding owners and responsible parties in the implementation of suitable measures that appropriately balance facility construction and use with improved safety and security of the facility occupants.

The Department of Homeland Security has implemented the Interagency Security Committee (ISC) Security Design Criteria. The ISC Security Design Criteria was developed to ensure that security issues are addressed during the planning, design, and construction of all new Federal Courthouses, new Federal Office Buildings, and major renovations. This federal criteria has been extended to also cover leased facilities. This document is for official use only and is not available to the general public.

Similarly, the Department of Defense (DoD) has implemented antiterrorism security requirements to meet its specific needs. Contained within the Unified Facilities Criteria (UFC) are the 4-xxx series of security engineering documents that deal with antiterrorism and physical security. In general, the UFC criteria is designed for use by the three services and other DoD agencies. The UFC DoD Minimum Antiterrorism Standard for Buildings Document (UFC 4-010-01) details the minimum building requirements including blast resistant requirements. This document has unrestricted availability when separated from the design explosive charges.

These documents were considered in the analysis of the SlenderWall system. The most common blast loading criteria seen in ARA's experience with blast analysis are from these documents and are as follows:

1. UFC Criteria - Charge Weight I (CWI) and Charge Weight II (CWII) at the conventional construction standoff distance with the assumptions of a primary gathering building as defined by the UFC. Table B1 from the UFC-010-01 shows the design standoffs that were used and is shown below.
    a. Designed for a low level of protection as defined by the UFC: Major deformation of non-structural elements and secondary structural members, but complete failure is unlikely. Majority of personal suffer significant injuries. There may be a few (<10%) fatalities.

Table B-1 Standoff Distances for New and Existing Buildings

Location	Building Category	Standoff Distance Requirements			
		Applicable Level of Protection	Conventional Construction Standoff Distance	Minimum Standoff Distance(1)	Applicable Explosive Weight (2)
Controlled Perimeter or Parking and Roadways without a Controlled Perimeter	Billeting and High Occupancy Family Housing	Low	45 m (3) (148 ft.)	25 m (3) (82 ft.)	I
	Primary Gathering Building	Low	45 m (3) (4) (148 ft.)	25 m (3) (4) (82 ft.)	I
	Inhabited Building	Very Low	25 m (3) (82 ft.)	10 m (3) (33 ft.)	I
Parking and Roadways within a Controlled Perimeter	Billeting and High Occupancy Family Housing	Low	25 m (3) (82 ft.)	10 m (3) (33 ft.)	II
	Primary Gathering Building	Low	25 m (3) (4) (82 ft.)	10 m (3) (4) (33 ft.)	II
	Inhabited Building	Very Low	10 m (3) (33 ft.)	10 m (3) (33 ft.)	II
Trash Containers	Billeting and High Occupancy Family Housing	Low	25 m (82 ft.)	10 m (33 ft.)	II
	Primary Gathering Building	Low	25 m (82 ft.)	10 m (33 ft.)	II
	Inhabited Building	Very Low	10 m (33 ft.)	10 m (33 ft.)	II

(1) Even with analysis, standoff distances less than those in this column are not allowed for new buildings, but are allowed for existing buildings if constructed/retrofitted to provide the required level of protection at the reduced standoff distance.
(2) See UFC 4-010-02, for the specific explosive weights (kg/pounds of TNT) associated with designations – I and II. UFC 4-010-02 is For Official Use Only (FOUO)
(3) For existing buildings, see paragraph B-1.1.2.2 for additional options.
(4) For existing family housing, see paragraph B-1.1.2.2.3 for additional options.

2. ISC Criteria – Non-load bearing walls must be designed to a peak design pressure and impulse which is defined by the criteria. Also ensure that the walls are capable of resisting the dynamic reactions from the windows.
    a. Designed for medium protection as defined by the ISC Criteria: The Facility or protected space will sustain a significant degree of damage, but the structure should be reusable. Some casualties may occur and assets may be damaged. Building elements other than major structural elements may require replacement.

The blast loads used in the analysis were explosive weights I and II listed in the UFC 4-010-01 at the conventional construction standoff distances listed in Table B-1 for a primary gathering building. These blast loads encompass the ISC Medium Level of Protection design load. Additionally, although the labels for the stated levels of protection differ for the two criteria, the description of the type and amount of damage is similar. Therefore, it was unnecessary to analyze the system explicitly for the ISC Medium Level of Protection design load.

Discussion of SlenderWall Blast Resistant Design

The SlenderWall system is a lightweight precast panel system which can likely be used for blast load applications and may require minimal design changes to meet certain blast requirements. For this analysis, only one panel size was examined which is shown in Figure 2. The analysis does not address all configurations, but does show that the design is feasible for blast load applications.

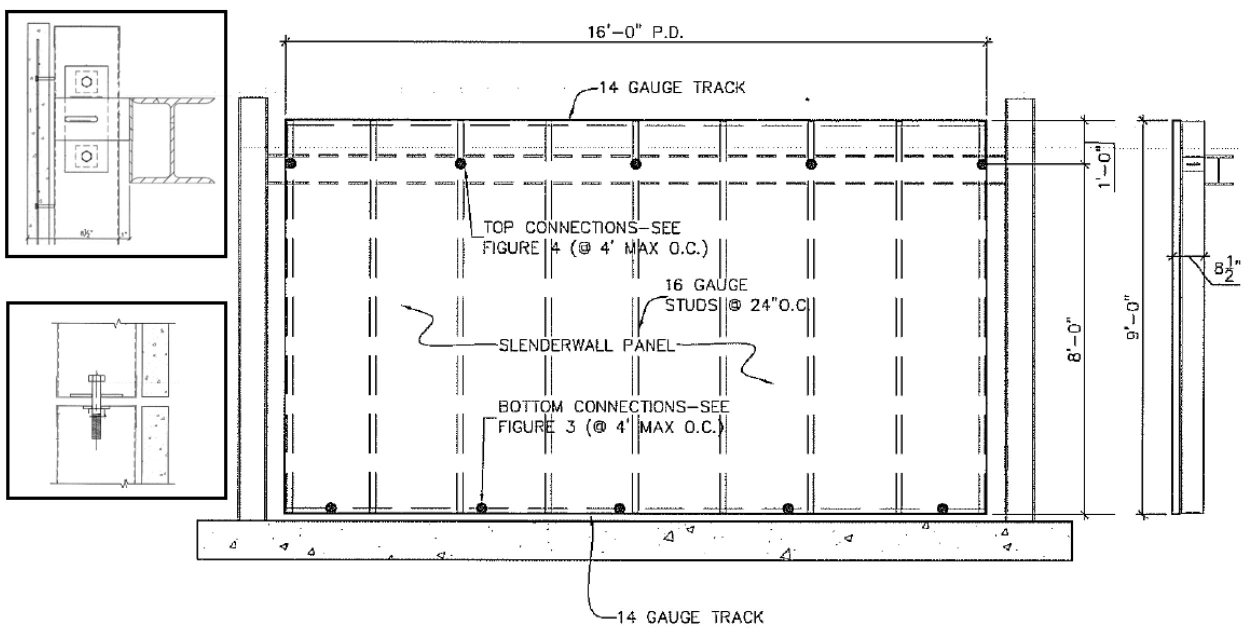

Figure 2. SlenderWall system analyzed.

The SlenderWall product design employs a number of components that aid in the blast resistance of the system. Energy is absorbed through the plastic deformation of the system components. The 2-inch thick precast with welded wire mesh offers the first load resisting system. Initially, the mass of the precast resists the short duration load due to its relatively high inertia.

Additionally, yielding of the wire mesh dissipates some of the energy. The remaining load is transferred to the steel studs via 1/4-inch Nelson studs. The steel studs also deflect and yield which absorbs additional energy. The remaining load is then transferred to the connections and into the supporting structure.

Although there is significant yielding in the wire mesh, and the steel studs the yielding remains within acceptable limits. The damage suffered by the SlenderWall system should not pose a significant hazard to occupants that may be interior to the system and will meet the level of protection specified in the criteria that was discussed earlier.

Due to the various panel dimensions that may be used for the product final application, the blast analysis proposed herein should be considered conceptual analysis only and should not be considered a "one size fits all" design. Additionally, due to the complexity of the system and the simplified analysis methods used, conservative deflection limits and stress limits were used in the analysis to limit the possibility of unaccounted response modes controlling the design.

Complex response modes such as buckling and web crippling are possible with the type of construction used on the panels, but were only addressed in a simplified fashion. Significant insight to these response modes can be provided using more in-depth analysis such as finite element analysis and/or explosive testing. In that case, the system could be designed to less stringent response limits and could reduce required material.

Results

The analysis was performed using single degree of freedom (SDOF) analysis and simplified hand calculations. For the SDOF analysis, both CWI and CWII were examined, but only the worst case response is included in this document. Additionally, generally components were analyzed using two types of assumptions: assumptions that will ensure a conservative member response (i.e. ductility and rotation values) and assumptions to ensure conservative member reaction loads.

An analysis of the 2-inch precast panel was performed initially. The loads from this analysis were then applied to the Nelson studs. Next, the steel studs were analyzed using the loads applied to the precast. The support reactions from this analysis were then resulting from the track as well as the welds which connect the stud to the track. Analysis of the connections to the supporting structure was not included since it may vary greatly based on the application of the system.

Response limits for this analysis were typically obtained from a U.S. Army corps of Engineers document authorized by the Protective Design Center's (PDC) titled Single Degree of Freedom Structural Response Limits for Antiterrorism Design (PDC-TR-06-08) released on October 20, 2006. This document designates ductility and rotation limits for specific building construction material. ARA has also used its experience to designate additional limits not specified in the PDC document. The response limits for reinforced concrete and metal studs are shown in Table 4-1 and 4-6 of the PDC document and are shown below.

The precast was limited to a B2 component damage level. This was chosen since the precast is susceptible to spalling (throwing fragments into occupied space) and limiting spalling is desired. However, a B3 limit was applied to the steel studs/track since avoiding failure of the component is the main goal. Table 2-4 and Table 3-1 from the PDC document define the component damage limits and are shown below.

Table 4-1 Response Limits for Reinforced Concrete [1]

Member		B1		B2		B3		B4	
		μ	θ	μ	θ	μ	θ	μ	θ
Flexure	No shear reinforcing/ without tension membrane	1	-	-	2°	-	5°	-	10°
	With compression face steel reinforcement and shear reinforcing/without tension membrane [2]	1	-	-	4°	-	6°	-	10°
	With tension membrane (L/h>=5) [3, 4]	1	-	-	6°	-	12°	-	20°
Combined Flexure & Compression [5]	No shear reinforcing/ without tension membrane	1	-	-	2°	-	2°	-	2°
	With compression face steel reinforcement and shear reinforcing/without tension membrane [2]	1	-	-	4°	-	4°	-	4°
Compression [5, 6]	Walls & Seismic Columns	0.9	-	1	-	2	-	3	-
	Non-Seismic Columns	0.7	-	0.8	-	0.9	-	1	-
Tension or Combined Flexure & Tension		No response limits in this report, see SBEDS Methodology Manual							

Table 4-6 Flexural Response Limits for Cold Formed Steel [1]

Member		B1		B2		B3		B4	
		μ	θ	μ	θ	μ	θ	μ	θ
Girts & Purlins [2]	No Tension Membrane Action	1	-	-	3°	-	10°	-	20°
	With Tension Membrane Action	1	-	-	4°	-	12°	-	20°
Metal Studs [2,3]	Top slip track studs walls [4]	0.5	-	0.8	-	0.9	-	1	-
	Studs connected top & bottom [5]	0.5	-	1	-	2	-	3	-
	Top and bottom of studs anchored to develop full tensile membrane capacity of the stud [6]	0.5	-	1	0.5°	2	2°	5	5°
One-Way Corrugated Metal Deck	Full tensile membrane capacity [7]	1	-	3	3°	6	6°	10	12°
	Some tensile membrane capacity [8]	1	-	-	1°	-	4°	-	8°
	Limited tensile membrane capacity [9]	1	-	1.8	1.3°	3	2°	6	4°
Standing Seam Metal Deck		1	-	1.8	1.3°	3	2°	6	4°

Table 2-4 Component Damage Levels

Component Damage Level	Description of Component Damage
Blowout	Component is overwhelmed by the blast load causing debris with significant velocities
Hazardous Failure	Component has failed, and debris velocities range from insignificant to very significant
Heavy Damage	Component has not failed, but it has significant permanent deflections causing it to be unrepairable
Moderate Damage	Component has some permanent deflection. It is generally repairable, if necessary, although replacement may be more economical and aesthetic
Superficial Damage	Component has no visible permanent damage

Table 3-1 Component Damage Levels Relationship to Response Limits

Component Damage Level	Relationship to Response Limits
Blowout	Response greater than B4.
Hazardous Failure	Response between B3 and B4
Heavy Damage	Response between B2 and B3.
Moderate Damage	Response between B1 and B2.
Superficial Damage	Response is less than B1.

Precast Concrete

The 5000 psi normal weight precast concrete for the system is 2 inches thick and spans 24 inches between steel studs with WWF 6x6 W2.9xW2.9 mesh. At the steel stud locations, there are 1/4-inch Nelson studs attaching the precast to the concrete at 24 inches on center. The precast concrete panel was analyzed with two separate methods; as a one way slab and as a flat slab with columns (the Nelson studs). The chosen response limit for the precast was 2 degrees rotation. ARA also desired to keep the ductility below 10. The analyzed precast concrete met the required limits with max responses of 0.10 degrees of rotation, a ductility of 1.83, and resulted in a max shear of 4,471 lb inward load and 1,734 lb rebound load per Nelson stud.

Nelson Studs

The Nelson studs were 1/4 inches in diameter and 1-3/4 inches long spaced at 24 inches on center. The inward load of 4471 lb will likely punch out the concrete on the exterior side of the precast, but after 1/2 inch movement the precast will bare against the steel stud and should not enter further into the occupied space of a building. The rebound load from the concrete per stud was 1,724 lb. The analysis of the Nelson studs embedded 1-1/4 inches into the concrete resulted in a tensile capacity of 1,773 lb. Although the capacity of the Nelson stud is higher than the rebound load in an undamaged condition, the panel may disengage the stud due to the damage resulting from the initial inward response.

One way to address the rebound issue is to decreases the Nelson stud spacing to reduce the load on each stud. The required spacing is dependent on the applied blast loads. Another option is to shim the 1/2-inch gap between the stud and the precast at the Nelson stud locations. This will prevent the Nelson stud from punch through the precast under the inward load. The 1/2-inch thick shim can be composed of wood, plastic or metal and should be a minimum of a 1-1/4-inch square shim. A more detailed analysis may also be performed to better understand how the panel will respond to the rebound loads. The current analysis is based on the stud manufacturers design charts. It should be noted that many project specifications have no rebound blast load requirements and it may be ok to fail the panel in rebound.

Studs

600S162-54 steel studs at 9'-0" long and spaced 24" on center are used for the analyzed system. A ductility limit of 2 was the flexural response limit used for cold formed metal studs. The blast load applied to the precast panel was applied to the steel studs and analyzed using SDOF. The system was modeled with simple supports. The stud's performance was below the allowable limit with a max rotation of 1.89 degrees, and a ductility of 1.92. The connection of the precast to the stud is sufficient to ensure some composite action. Therefore, to determine a conservative estimate of the end reactions from the stud, the vertical steel studs and the precast panes were treated as a fully composite section and analyzed as a pinned-pinned one-way system. The max end shear at the attachment to the steel tracks was 5270 lb. With this load, a total 4 inch long 1/8-inch fillet weld (E70xx) long per stud connection. According to the provided details the current total weld length at these connections is adequate with a total combined length of 4.125 inches.

Track

The steel tracks used were 600T125-68 tracks with anchor points every 4 feet. As with the studs the track ductility limit is 2. The track was loaded with the time varying end reactions from the stud analysis and modeled as a fixed-simple beam which is consistent with the end panels. The tracks met the requirements with a max rotation of 0.133 degrees, ductility of 0.969, and max end shear of 4,583 lb.

The connections to the supporting structure will be required to handle the end loads from the track as well as from the studs. For this panel system, the peak design load at the connections is, therefore, approximately 15,000 lb per connection.

Summary and Recommendations

Overall, for typical UFC explosive weights I and II with conventional standoff distances, the SlenderWall system performs well. The analysis included herein show that the SlenderWall performs well for a representative blast load application. A summary table of the component response is seen below.

	Rotation	Ductility	Member Reactions
Precast Panel	0.10 deg.	1.83	4,471 lb
Steel Stud	1.89 deg.	1.92	5,270 lb
Track	0.13 deg	0.97	4,583 lb

The total end reaction at the connections to the structure is approximately 15,000 lb.

Nelson stud spacing shall be determined on a case-by-case basis, depending on the blast requirement, final panel configurations and light gauge stud spacing for the project under consideration. Localized punching shear at the Nelson studs must be analyzed to ensure the panels satisfy both the initial blast as well any rebound requirement, if applicable.

For the case study noted in this report, the Nelson stud anchor spacing would need to be less than the standard 24 inches o.c. If the designers wish to maintain the standard 24-inch Nelson stud spacing, another option would be to insert 1 ¼ inch square plastic shims at each Nelson stud to reduce the effects of localized punching shear. The designer should evaluate each project separately to determine which of these options is the most economical option.

This report presented a simplified analysis of a given panel geometry using simplified models for the purpose of estimating global response and identifying potential failure modes. Future studies could be performed using Finite Element Analysis or explosive testing to determine system responses that simplified methods would be less likely to predict. However, it should be noted that the methods used in this report are the same methods commonly utilized on façade design for both precast and curtain wall systems.

As is true with any blast-rated building, the Design Team must evaluate each project on a case-by-case basis. Factors such as stand-off, building configuration and panel geometry may all need to be factored in to the blast response evaluation.

Under the blast conditions analyzed in this report, the Slenderwall panels performed remarkably well. The global response of the system indicates that the Slenderwall panel system is an extremely viable option when a moderate level blast design of the façade is required. The results of the analysis demonstrate the global response of the system, which confirm that the overall system performs satisfactorily and may be used in blast applications.

Contact Information

Analysis Team

Timothy Floyd
Security Engineer
Applied Research Associates, Inc.
119 Monument Place
Vicksburg, MS 39180
Email: tfloyd@ara.com
Phone: (601) 638-5401
Fax: (601) 634-0631

Charles C. Ellison, P.E.
Senior Security Engineer
Applied Research Associates, Inc.
119 Monument Place
Vicksburg, MS 39180
Phone: (601) 638-5401
Fax: (601) 634-0631

James T. Brokaw
Director of Security Engineering
Applied Research Associates, Inc.
119 Monument Place
Vicksburg, MS 39180
Email: jbrokaw@ara.com
Phone: (601) 638-5401
Fax: (601) 634-0631

Local Contacts

Steve Ott, PE
VP Engineering
5119 Catlett Road / PO Box 300
Midland, VA 22728
Phone: (540) 439-3266
Fax: (540) 439-1232

Appendix

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Single Degree Of Freedom (SDOF)
 Version 2.0 - Release April 2006
 Date = 06/25/2010
 Time = 15:04:04.099

 Slender Wall Test Panel CW I

                  ONE WAY SDOF ANALYSIS

   Boundary Condition for One Way System                 = pinned-fixed
   Load Condition for One Way System                     = uniform load
   Desired Response                                      =      plastic
   Load-Mass Factor                                      =         0.66
   Resistance Factors
         Midspan                                         =         4.00
         Edge                                            =         8.00
   Stiffness Factor                                      =       160.00
   Span, in                                              =        24.00

                 R/C MATERIAL PROPERTIES

   Concrete Modulus of Elasticity, psi                   =   3828427.12
   Concrete Compressive Strength (fc), psi               =      5000.00
   Steel Yield Strength (fy), psi                        =     60000.00
   Concrete Unit Weight, pcf                             =       145.00
   Dynamic Strength Factor (fc)                          =         1.20
   Dynamic Strength Factor (fy)                          =         1.20

                 R/C SECTION PROPERTIES

   Section Depth, in                                     =         2.00
   Minimum steel ratio %, As/bd                          =        0.360
   Depth to inside steel, in                             =         1.00
   Inside steel ratio %, As/bd                           =        0.483
   Depth to outside steel, in                            =         1.00
   Outside steel ratio %, As/bd                          =        0.483
   Moments of Inertia
       Uncracked Moment of Inertia, in^4                 =        0.667
       Cracked Moment of Inertia, in^4                   =        0.027
   Additional dead load, psi                             =         0.00
   Additional live load, psi                             =         0.00

                 CALCULATED PROPERTIES

   Mass, psi*msec^2/in                                   =       434.68
   Effective Mass, psi*msec^2/in                         =       286.89
   Maximum positive moment per unit width, in-lbf/in     =       335.87
   Maximum negative moment per unit width, in-lbf/in     =       335.87
   Effective Moment of Inertia per unit width, in^4/in   =         0.35
   Maximum Resistance per unit area, psi                 =         7.00
   Stiffness per unit area, psi/in                       =       639.95
   Yield Deflection, in                                  =         0.01
   Natural Period, msec                                  =         4.21

        RESISTANCE FUNCTION               LOADING FUNCTION
         (psi)        (in)               (msec)       (psi)
          0.00        0.00
          7.00        0.01
          7.00       10.93

                   SDOF PARAMETERS
   Critical Damping Ratio, %                             =        0.200
   Time Step, msec                                       =        0.008

                    SDOF RESULTS
```

Time of Yield, msec	=	1.42
Ductility	=	1.373
Rotation	=	0.072
Peak Dynamic Shear lbf/in	=	90.40
Last time, msec	=	420.68

	MAXIMUMS		MINIMUMS	
	Value	Time	Value	Time
ACC =	0.1661E-01	0.0000E+00	-0.1005E-01	0.2373E+01
VEL =	0.1066E-01	0.1026E+01	-0.7137E-02	0.3424E+01
DISP =	0.1501E-01	0.2331E+01	-0.1747E-03	0.1715E+02

```
Single Degree Of Freedom (SDOF)
 Version 2.0 - Release April 2006
 Date = 06/25/2010
 Time = 15:04:04.380

 Slender Wall Test Panel CW II

                  ONE WAY SDOF ANALYSIS

   Boundary Condition for One Way System                  = pinned-fixed
   Load Condition for One Way System                      = uniform load
   Desired Response                                       =      plastic
   Load-Mass Factor                                       =         0.66
   Resistance Factors
         Midspan                                          =         4.00
         Edge                                             =         8.00
   Stiffness Factor                                       =       160.00
   Span, in                                               =        24.00

                 R/C MATERIAL PROPERTIES

   Concrete Modulus of Elasticity, psi                    =   3828427.12
   Concrete Compressive Strength (fc), psi                =      5000.00
   Steel Yield Strength (fy), psi                         =     60000.00
   Concrete Unit Weight, pcf                              =       145.00
   Dynamic Strength Factor (fc)                           =         1.20
   Dynamic Strength Factor (fy)                           =         1.20

                 R/C SECTION PROPERTIES

   Section Depth, in                                      =         2.00
   Minimum steel ratio %, As/bd                           =        0.360
   Depth to inside steel, in                              =         1.00
   Inside steel ratio %, As/bd                            =        0.483
   Depth to outside steel, in                             =         1.00
   Outside steel ratio %, As/bd                           =        0.483
   Moments of Inertia
       Uncracked Moment of Inertia, in^4                  =        0.667
       Cracked Moment of Inertia, in^4                    =        0.027
   Additional dead load, psi                              =         0.00
   Additional live load, psi                              =         0.00

                 CALCULATED PROPERTIES

   Mass, psi*msec^2/in                                    =       434.68
   Effective Mass, psi*msec^2/in                          =       286.89
   Maximum positive moment per unit width, in-lbf/in      =       335.87
   Maximum negative moment per unit width, in-lbf/in      =       335.87
   Effective Moment of Inertia per unit width, in^4/in    =         0.35
   Maximum Resistance per unit area, psi                  =         7.00
   Stiffness per unit area, psi/in                        =       639.95
   Yield Deflection, in                                   =         0.01
   Natural Period, msec                                   =         4.21

        RESISTANCE FUNCTION               LOADING FUNCTION
         (psi)        (in)               (msec)       (psi)
          0.00        0.00
          7.00        0.01
          7.00       10.93

                   SDOF PARAMETERS
   Critical Damping Ratio, %                              =        0.200
   Time Step, msec                                        =        0.008

                    SDOF RESULTS
   Time of Yield, msec                                    =         1.25
   Ductility                                              =        1.825
   Rotation                                               =        0.095
   Peak Dynamic Shear  lbf/in                             =        92.43
   Last time, msec                                        =       420.68
```

	MAXIMUMS Value	Time	MINIMUMS Value	Time
ACC =	0.2011E-01	0.0000E+00	-0.9609E-02	0.2777E+01
VEL =	0.1258E-01	0.1010E+01	-0.7289E-02	0.3828E+01
DISP =	0.1995E-01	0.2684E+01	0.0000E+00	0.0000E+00

Flat Slab- Slender Wall

Material properties

$f_c := 5000\,psi$	$dyn_y := 1.2$	Compressive strength of concrete
$f_y := 60000\,psi$	$dyn_c := 1.2$	Yield strength of steel
$\rho_c := 145 \cdot \frac{lbf}{ft^3}$	$\rho_c = 0.084 \frac{lbf}{in^3}$	Density of concrete
$\rho_s := 490 \cdot \frac{lbf}{ft^3}$	$\rho_s = 0.284 \frac{lbf}{in^3}$	Density of steel
$E_c := \left(40000\sqrt{\frac{f_c}{psi}} + 10^6\right) \cdot \left(\frac{\rho_c \cdot ft^3}{145 \cdot lbf}\right)^{1.5} \cdot psi$	$E_c = 3828427\,psi$	Modulus of elasticity of the concrete

Slab properties

$h := 2 \cdot in$	$h = 2\,in$	Thickness of slab
$a := 2 \cdot ft$	$a = 24\,in$	Span
$d := h - 1 \cdot in$	$d = 1\,in$	Depth of steel reinforcement
$b := 1.2 \cdot in$	$b = 1.2\,in$	Width of column capital
$A_{ct} := 0.058 \frac{in^2}{ft}$	$A_{cb} := 0.058 \frac{in^2}{ft}$	Area of steel per unit width, column strip
$A_{mt} := 0.058 \frac{in^2}{ft}$	$A_{mb} := 0.058 \frac{in^2}{ft}$	Area of steel per unit width, middle strip
$DL := 0 \cdot \frac{lbf}{ft^2}$	$DL = 0\,psi$	Additional Dead Load
$LL := 0.00 \frac{lbf}{ft^2}$	$LL = 0\,psi$	Live Load

Calculated properties

$aspect := \frac{b}{a}$	$aspect = 0.05$	Aspect Ratio
$A_{avg} := \frac{A_{ct} + A_{cb} + A_{mt} + A_{mb}}{4}$	$A_{avg} = 0.058 \frac{in^2}{ft}$	Average Area of Steel
$\rho_{avg} := \frac{A_{avg}}{d}$	$\rho_{avg} = 0.00483$	Steel Ratio, average
$\rho_{ct} := \frac{A_{ct}}{d}$ $\quad \rho_{ct} = 0.00483$ $\quad \rho_{cb} := \frac{A_{cb}}{d}$	$\rho_{cb} = 0.00483$	Steel Ratio, column strip
$\rho_{mt} := \frac{A_{mt}}{d}$ $\quad \rho_{mt} = 0.00483$ $\quad \rho_{mb} := \frac{A_{mb}}{d}$	$\rho_{mb} = 0.00483$	Steel Ratio, middle strip
$I := \frac{5.5}{2} \cdot d^3 \cdot \rho_{avg} + \frac{1}{24} \cdot h^3$	$I = 0.347 \frac{in^4}{in}$	Moment of inertia per unit width
$M_{ct} := \rho_{ct} \cdot f_y \cdot d^2 \cdot \left(1 - .59 \cdot \rho_{ct} \cdot \frac{f_y}{f_c}\right)$	$M_{ct} = 280.076 \frac{in \cdot lbf}{in}$	Ultimate moment capacity per unit width, column strip, top
$M_{cb} := \rho_{cb} \cdot f_y \cdot d^2 \cdot \left(1 - .59 \cdot \rho_{cb} \cdot \frac{f_y}{f_c}\right)$	$M_{cb} = 280.076 \frac{in \cdot lbf}{in}$	Ultimate moment capacity per unit width, column strip, bottom
$M_{mt} := \rho_{mt} \cdot f_y \cdot d^2 \cdot \left(1 - .59 \cdot \rho_{mt} \cdot \frac{f_y}{f_c}\right)$	$M_{mt} = 280.076 \frac{in \cdot lbf}{in}$	Ultimate moment capacity per unit width, middle strip, top
$M_{mb} := \rho_{mb} \cdot f_y \cdot d^2 \cdot \left(1 - .59 \cdot \rho_{mb} \cdot \frac{f_y}{f_c}\right)$	$M_{mb} = 280.076 \frac{in \cdot lbf}{in}$	Ultimate moment capacity per unit width, middle strip, bottom

$$ratio := \begin{pmatrix} 0.05 \\ 0.10 \\ 0.15 \\ 0.20 \\ 0.25 \end{pmatrix} \quad kf := \begin{pmatrix} 208 \\ 230 \\ 252 \\ 276 \\ 302 \end{pmatrix} \quad rf := \begin{pmatrix} 4.2 \\ 4.4 \\ 4.6 \\ 4.8 \\ 5.0 \end{pmatrix} \quad K_{LM} := 0.64$$

Transformation factors from Biggs

$kf := \text{linterp}(ratio, kf, aspect)$	$kf = 208$	Elastic spring rate factor
$rf := \text{linterp}(ratio, rf, aspect)$	$rf = 4.2$	Elastic resistance factor
$k_E := \frac{kf \cdot E_c \cdot I}{a^2 \cdot a^2}$	$k_E = 831.953 \frac{psi}{in}$	Elastic spring rate per unit area
$R_m := \frac{rf \cdot (M_{ct} + M_{cb} + M_{mt} + M_{mb})}{a^2}$	$R_m = 8.169 psi$	Maximum elastic-plastic resistance per unit area
$m_t := \frac{h \cdot \rho_c}{g} + \frac{A_{avg} \cdot \rho_s}{g} + \frac{DL}{g}$	$m_t = 438.228 \frac{psi \cdot (msec)^2}{in}$	Total mass per unit area
$F_{in} := m_t \cdot g + LL$	$F_{in} = 0.169 psi$	Initial gravity load
$R_{adj} := R_m - F_{in}$	$R_{adj} = 8 psi$	Resistance adjusted for gravity
$T := 2 \cdot \pi \cdot \sqrt{\frac{K_{LM} \cdot m_t}{k_E}}$	$T = 3.648 msec$	Natural period
$c_{cr} := 2 \cdot \sqrt{k_E \cdot K_{LM} \cdot m_t}$	$c_{cr} = 966.094 \frac{psi \cdot msec}{in}$	Critical damping coefficient
$M := K_{LM} \cdot m_t$	$M = 280.46567 \frac{psi \cdot (msec)^2}{in}$	Effective mass per unit area

SDOF Parameters

$K := k_E \cdot \frac{in}{psi}$ $\quad K = 831.953$ Elastic spring rate per unit area

$R_m := R_m \cdot \frac{1}{psi}$ $\quad R_m = 8.169$ Maximum elastic-plastic resistance per unit area

$y_{el} := \frac{R_m}{K}$ $\quad y_{el} = 9.819 \times 10^{-3}$ Yield displacement

$F_{in} := F_{in} \cdot \frac{1}{psi}$ $\quad F_{in} = 0.169$ Initial gravity load

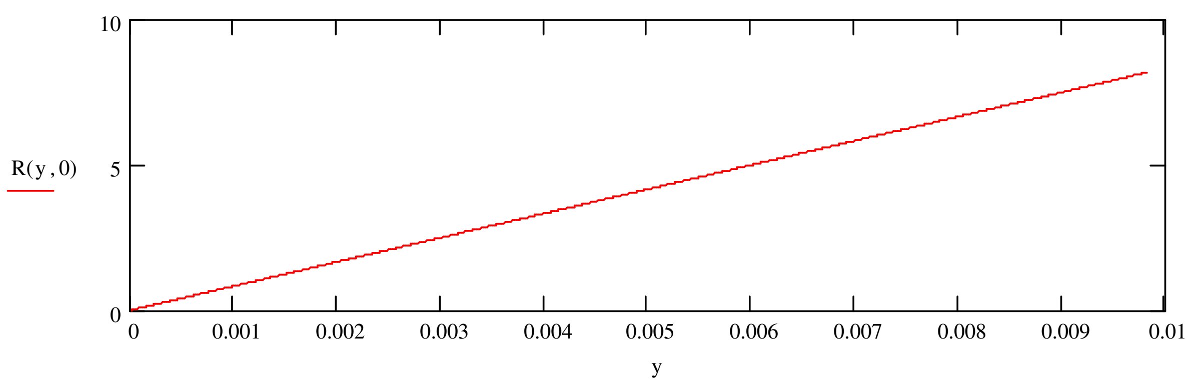
$y_{in} := \frac{F_{in}}{K}$ $\quad y_{in} = 2.034 \times 10^{-4}$ Initial displacement due to gravity

$c_{cr} := c_{cr} \cdot \frac{in}{psi \cdot msec}$ $\quad c_{cr} = 966.094$ Critical damping coefficient

$M := K_{LM} \cdot \frac{m_t}{\frac{psi \cdot (msec)^2}{in}}$ $\quad M = 280.46567$ Effective mass

$R(y_1, y_2) := K \cdot (y_1 - y_2)$ Resistance Function

$y := 0, \frac{y_{el}}{1000} .. y_{el}$



Loading Function (CW II)

$P_{max} := CW2_{pressure}$ Maximum load

$t_d := CW2_{duration}$ Load duration

$$F_1(t) := \frac{\begin{cases} P_{max} - \frac{P_{max} \cdot t}{\left(\frac{t_d}{msec}\right)} & \text{if } t < \frac{t_d}{msec} \\ 0 \cdot psi & \text{otherwise} \end{cases}}{psi}$$

Forcing function

SDOF Calculations

$N := 2000$ Number of time steps

$dur := 50$ Calculation time (msec)

$y := \begin{pmatrix} 0 \\ 0 \\ -y_{in} \end{pmatrix}$ Initial values

$$D_1(t,y) := \begin{bmatrix} y_1 \\ \frac{1}{M}\cdot\left(F(t) + F_{in} - R(y_0, y_2) - 0.0002c_{cr}\cdot y_1\right) \\ \left| \begin{array}{l} y_1 \text{ if } \left[(y_0 - y_2) > y_{el}\right]\cdot(y_1 > 0) \\ y_1 \text{ if } \left[(y_0 - y_2) < -y_{el}\right]\cdot(y_1 < 0) \\ 0 \text{ otherwise} \end{array} \right. \end{bmatrix}$$

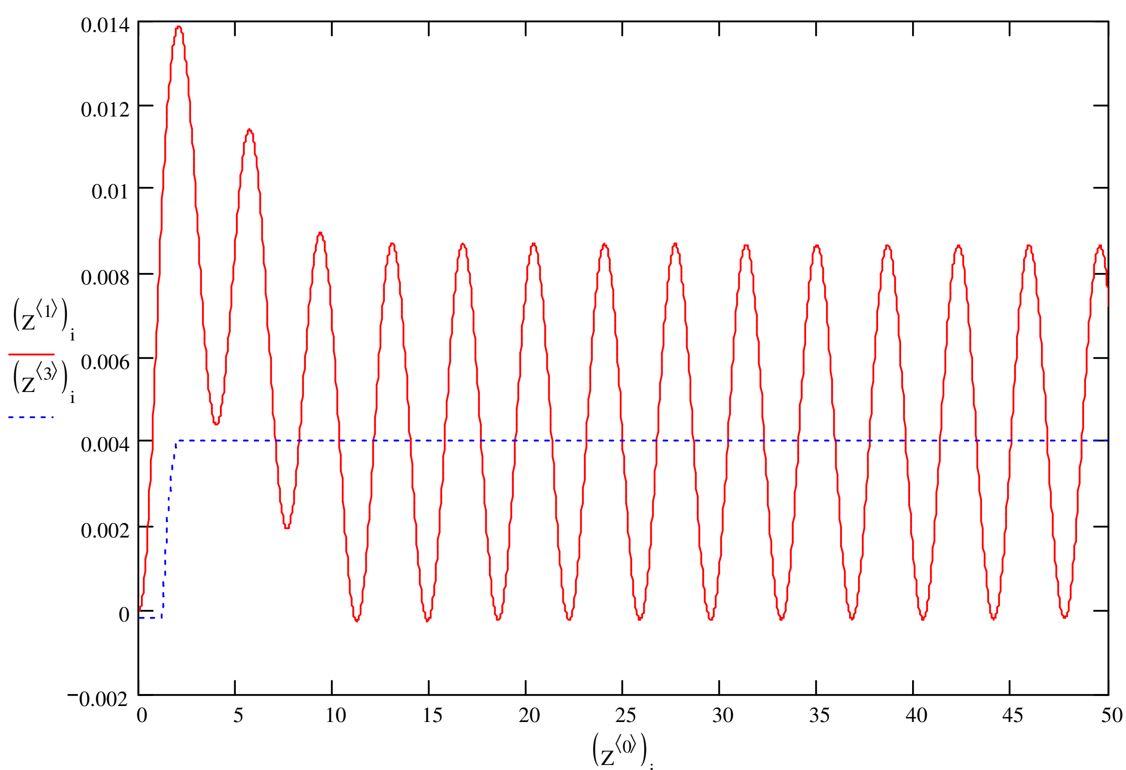
System of first order differentia equations

$Z := \text{rkfixed}(y, 0, dur, N, D_1)$ $\quad i := 0..N$

$y_m := \max\left(Z^{\langle 1 \rangle}\right)$ $\quad y_m = 0.0139$ Maximum displacement

$\mu_y := \dfrac{y_m + y_{in}}{y_{el}}$ $\quad \mu_y = 1.433$ Ductility

$\theta := \text{atan}\left(\dfrac{2\cdot y_m\cdot in}{a}\right)$ $\quad \theta = 0.066\text{deg}$ Rotation



$$n := \left| \begin{array}{l} y_{max} \leftarrow 0 \\ \text{for } i \in 1..N \\ \quad \text{if } \left(Z^{\langle 1\rangle}\right)_i > y_{max} \\ \quad \quad \left| \begin{array}{l} y_{max} \leftarrow \left(Z^{\langle 1\rangle}\right)_i \\ t_{max} \leftarrow \left(Z^{\langle 0\rangle}\right)_i \\ n \leftarrow i \end{array} \right. \\ n \end{array} \right.$$

$n = 82$ Time step of max response

$t_{max} := \left(Z^{\langle 0\rangle}\right)_n$ $t_{max} = 2.050$ Time of max. response

$$R_f(i) := \left| \begin{array}{ll} 0.84 & \text{if } \left| R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right] \right| < R_m \\ 0.86 & \text{otherwise} \end{array} \right.$$

$R_f(n) = 0.86$

$$F_f(i) := \left| \begin{array}{ll} 0.16 & \text{if } \left| R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right] \right| < R_m \\ 0.14 & \text{otherwise} \end{array} \right.$$

$F_f(n) = 0.14$

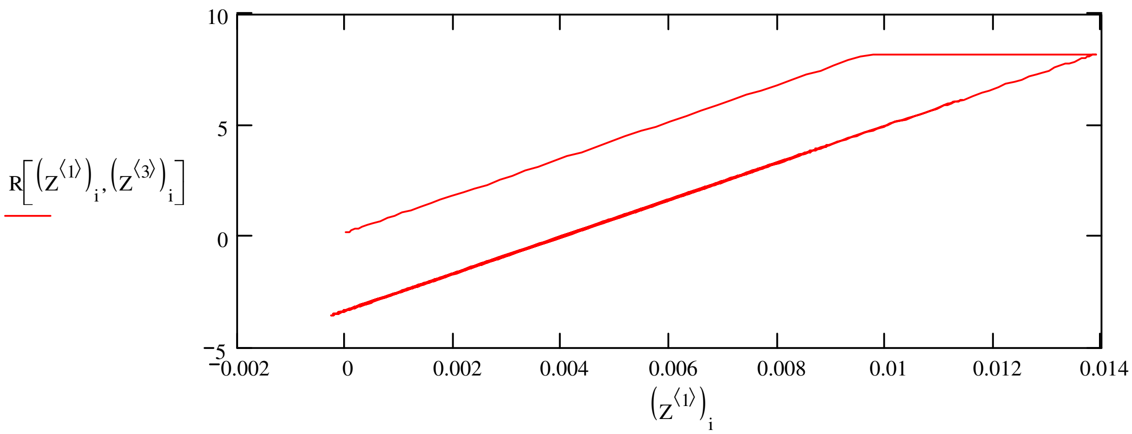
Load on column capital

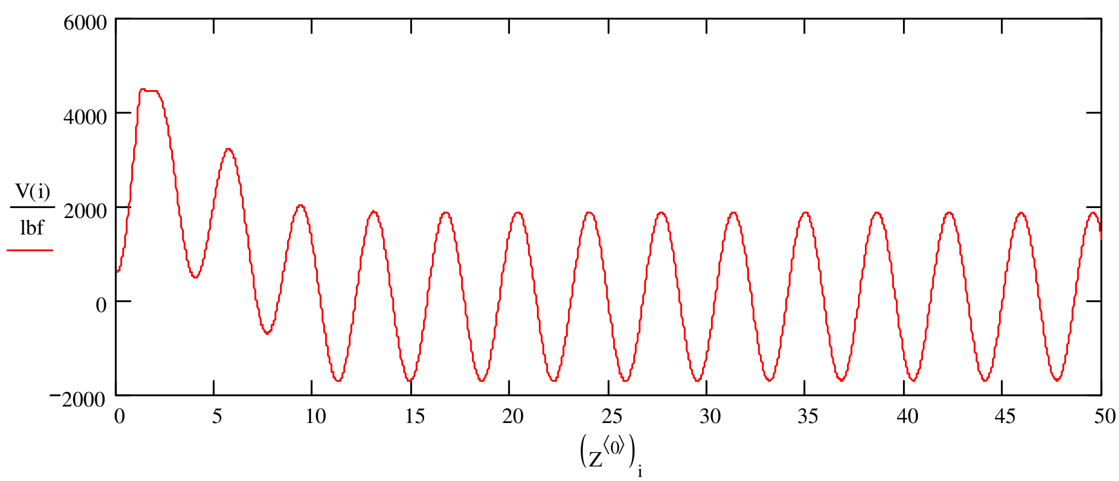
$$V(i) := \left[R_f(i)\cdot R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right] + F_f(i)\cdot F\left[\left(Z^{\langle 0\rangle}\right)_i\right] + F_{in}\right]\cdot a\cdot a\cdot psi$$

$V(n) = 4530\text{lbf}$ includes gravity

$$V(i) := \left[R_f(i)\cdot R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right] + F_f(i)\cdot F\left[\left(Z^{\langle 0\rangle}\right)_i\right]\right]\cdot a\cdot a\cdot psi$$

$V(n) = 4433\text{lbf}$ without gravity





Tension and Shear Capacity of Nelson Studs

Stud and Concrete Properties

$f_c := 5000\,psi$	Concrete compressive strength	$\phi_c := 0.85$	Concrete strength design factor listed in manual
$f_u := 60000\,psi$	Nelson stud ultimate strength	$\phi_s := 0.90$	Steel strength design factor listed in manual
$\rho_c := 145\cdot\frac{lbf}{ft^3}$	Unit weight of concrete	$C := 1.0$	Constant for Concrete Type (1.0=Normal, 0.75=Light, 0.85=Sand Light)
$n_r := 1$	Number of studs in row	$n_c := 1$	Number of studs in column
$S_r := 24\cdot in$	Row spacing of nelson studs	$S_c := 24\cdot in$	Column spacing of nelson studs
$E_{front} := 5\cdot in$	Distance to front edge	$E_{back} := 5\cdot in$	Distance to back edge
$E_{left} := 100\cdot in$	Distance to left edge	$E_{right} := 100\cdot in$	Distance to right edge
$Depth := 24\cdot in$	Depth of concrete	$K := 4.0$	Nelson Stud constant listed in manual (Used in Concrete Calc.)

$Select := 1$ Stud number from following chart

$$\begin{pmatrix} D_s \\ L_s \\ D_h \\ L_t \\ L_e \end{pmatrix} :=$$

Number	Description	Stud Diameter	Head Length	Head Diameter	Length Before Weld	Length After Weld	Le
1	1/4 x 2-11/16 H4L	0.250	0.187	0.500	2.687	2.562	2.375
2	1/4 x 4-1/8 H4L	0.250	0.187	0.500	4.125	4.000	3.813
3	3/8 x 4-1/8 H4L	0.375	0.281	0.750	4.125	4.000	3.719
4	3/8 x 6-1/8 H4L	0.375	0.281	0.750	6.125	6.000	5.719
5	1/2 x 2-1/8 H4L	0.500	0.312	1.000	2.125	2.000	1.688
6	1/2 x 3-1/8 H4L	0.500	0.312	1.000	3.125	3.000	2.688
7	1/2 x 4-1/8 H4L	0.500	0.312	1.000	4.125	4.000	3.688
8	1/2 x 5-5/16 H4L	0.500	0.312	1.000	5.312	5.187	4.875
9	1/2 x 6-1/8 H4L	0.500	0.312	1.000	6.125	6.000	5.688
10	1/2 x 8-1/8 H4L	0.500	0.312	1.000	8.125	8.000	7.688
11	5/8 x 2-11/16 H4L	0.625	0.312	1.250	2.687	2.500	2.188
12	5/8 x 6-9/16 H4L	0.625	0.312	1.250	6.562	6.375	6.063
13	5/8 x 8-3/16 H4L	0.625	0.312	1.250	8.187	8.000	7.688
14	3/4 x 3-3/16 H4L	0.750	0.375	1.250	3.187	3.000	2.625
15	3/4 x 4-3/16 H4L	0.750	0.375	1.250	4.187	4.000	3.625
16	3/4 x 5-3/16 H4L	0.750	0.375	1.250	5.187	5.000	4.625
17	3/4 x 6-3/16 H4L	0.750	0.375	1.250	6.187	6.000	5.625
18	3/4 x 7-3/16 H4L	0.750	0.375	1.250	7.187	7.000	6.625
19	3/4 x 8-3/16 H4L	0.750	0.375	1.250	8.187	8.000	7.625
20	7/8 x 3-11/16 H4L	0.875	0.375	1.375	3.687	3.500	3.125
21	7/8 x 4-3/16 H4L	0.875	0.375	1.375	4.187	4.000	3.625
22	7/8 x 5-3/16 H4L	0.875	0.375	1.375	5.187	5.000	4.625
23	7/8 x 6-3/16 H4L	0.875	0.375	1.375	6.187	6.000	5.625
24	7/8 x 7-3/16 H4L	0.875	0.375	1.375	7.187	7.000	6.625
25	7/8 x 8-3/16 H4L	0.875	0.375	1.375	8.187	8.000	7.625

Select

$D_s := D_s\cdot in$ $L_s := L_s\cdot in$ $D_h := D_h\cdot in$ $L_t := L_t\cdot in$ $L_e := L_e\cdot in$

Calculate Single Stud Properties in Tension - Inward Load

Properties from Chart for Selected Stud

$L_t = 2.562\text{in}$ — Nelson stud total length after weld

$D_s = 0.250\text{in}$ — Nelson stud shank diameter

$D_h = 0.500\text{in}$ — Nelson stud head diameter

$L_s = 0.187\text{in}$ — Nelson stud head length

$L_e = 0.750\text{in}$ $\quad L_e := 0.75\text{in}$ $\quad$ only 3/4" from the exterior Wall — Nelson stud embedment depth

Check Concrete Depth

$$L_t := \begin{cases} L_t & \text{if } (L_t + 1.0\cdot\text{in} < \text{Depth}) \\ 0.0\cdot\text{in} & \text{otherwise} \end{cases} \qquad L_t = 2.562\text{in}$$

Tensile Capacity of Single Stud

$$T_{ue} := \frac{\phi_s \cdot f_u \cdot \pi \cdot D_s^{\,2}}{4} \qquad \boxed{T_{ue} = 2651\text{lbf}}$$

Tensile capacity of single stud (steel strength)

$$R_t := L_e + \frac{D_h}{2} \qquad R_t = 1.000\text{in}$$

Radius for full shear cone (Based on 45 deg. shear plane)

$$L_{cord}(\theta_1, \theta_2, R) := \int_{\theta_1}^{\theta_2} \sqrt{(-R\cdot\sin(\theta))^2 + (R\cdot\cos(\theta))^2}\, d\theta$$

Equation for cord length of a circle

$$A_{fc} := \sqrt{2}\cdot\int_{R_t - L_e}^{R_t} L_{cord}(0, 2\cdot\pi, R)\, dR \qquad A_{fc} = 4.165\text{in}^2$$

Surface area of full shear cone

$$T_{uc} := \phi_c \cdot C \cdot K \cdot A_{fc} \cdot \sqrt{f_c \cdot \text{psi}} \qquad \boxed{T_{uc} = 1001\text{lbf}}$$

Full tensile capacity of concrete (single stud, no reductions)

Calculate Single Stud Properties in Tension - Rebound Load

Properties from Chart for Selected Stud

$L_t = 2.562\text{in}$ — Nelson stud total length after weld

$D_s = 0.250\text{in}$ — Nelson stud shank diameter

$D_h = 0.500\text{in}$ — Nelson stud head diameter

$L_s = 0.187\text{in}$ — Nelson stud head length

$L_e = 1.063\text{in}$ $\quad L_e := 1.25\text{in} - 0.1875\text{in}$ $\quad$ only 3/4" from the exterior Wall — Nelson stud embedment depth

Check Concrete Depth

$$L_t := \begin{cases} L_t & \text{if } (L_t + 1.0\cdot\text{in} < \text{Depth}) \\ 0.0\cdot\text{in} & \text{otherwise} \end{cases} \qquad L_t = 2.562\text{in}$$

Tensile Capacity of Single Stud

$$T_{ue} := \frac{\phi_s \cdot f_u \cdot \pi \cdot D_s^{\,2}}{4} \qquad \boxed{T_{ue} = 2651\text{lbf}}$$

Tensile capacity of single stud (steel strength)

$$R_t := L_e + \frac{D_h}{2} \qquad R_t = 1.313\text{in}$$

Radius for full shear cone (Based on 45 deg. shear plane)

$$L_{cord}(\theta_1, \theta_2, R) := \int_{\theta_1}^{\theta_2} \sqrt{(-R\cdot\sin(\theta))^2 + (R\cdot\cos(\theta))^2}\, d\theta$$

Equation for cord length of a circle

$$A_{fc} := \sqrt{2}\cdot\int_{R_t - L_e}^{R_t} L_{cord}(0, 2\cdot\pi, R)\, dR \qquad A_{fc} = 7.376\text{in}^2$$

Surface area of full shear cone

$$T_{uc} := \phi_c \cdot C \cdot K \cdot A_{fc} \cdot \sqrt{f_c \cdot \text{psi}} \qquad \boxed{T_{uc} = 1773\text{lbf}}$$

Full tensile capacity of concrete (single stud, no reductions)

Check Nelson Stud Attachement to Steel Stud

Calculate Total Tensile Capacity of Vertical Metal Stud

$D_h = 0.5\text{in}$ — Bolt head diameter of nelson stud

$Fu_{vs} := 50000\text{psi}$ — Ultimate strength of vertical metal stud

$t_{mstud} := 0.0566\text{in}$ — Thickness of vertical metal stud

$$A_{vsc} := \pi\cdot(D_h + t_{mstud})\cdot t_{mstud} \qquad A_{vsc} = 0.099\text{in}^2$$

Area of Vertical Stud Shear Cone

$$T_{vs} := \frac{1}{\sqrt{3}}\cdot Fu_{vs}\cdot A_{vsc} \qquad \boxed{T_{vs} = 2857\text{lbf}}$$

Tensile capacity of vertical metal stud

Calculate Shearing through Precast Concrete - Inward Load

$P_p := 447\,\text{lbf}$ — Worst Case Load on Nelson Stud (assumes 24" Spacing)

$P_p = 0.85 f_c \cdot A_1$ $\qquad A_{req} := \dfrac{P_p}{0.85 f_c}$ $\qquad A_{req} = 1.052\,\text{in}^2$ — Bearing Area Required of Concrete:

$D_h := \sqrt{\dfrac{4 \cdot A_{req}}{\pi}}$ — Assumed Shim diameter

$L_e := 2\text{in}$ — Concrete Thickness Resisting load (the whole precast thickness can be used for shimmed case)

Shear Capacity of Concrete for Shimmed Condition (Assumes a 1/2" Diameter shim)

$R_t := L_e + \dfrac{D_h}{2}$ $\qquad R_t = 2.579\,\text{in}$ — Radius for full shear cone (Based on 45 deg. shear plane)

$L_{cord}(\theta_1, \theta_2, R) := \displaystyle\int_{\theta_1}^{\theta_2} \sqrt{(-R \cdot \sin(\theta))^2 + (R \cdot \cos(\theta))^2}\, d\theta$ — Equation for cord length of a circle

$A_{fc} := \sqrt{2} \cdot \displaystyle\int_{R_t - L_e}^{R_t} L_{cord}(0, 2 \cdot \pi, R)\, dR$ $\qquad A_{fc} = 28.055\,\text{in}^2$ — Surface area of full shear cone

$T_{uc} := \phi_c \cdot C \cdot K \cdot A_{fc} \cdot \sqrt{f_c \cdot psi}$ $\qquad \boxed{T_{uc} = 6745\,\text{lbf}}$ — Full tensile capacity of concrete

Pinned-Pinned One-way Beam

$msec := 10^{-3} \cdot sec$

$f_y := 1.2 \cdot (5\ \ 33\ \ 33\ \ 33\ \ 33\ \ 33)^T \cdot 1000 \cdot psi$ Yield Stress

$E := (3.828\ \ 29\ \ 29\ \ 29\ \ 29\ \ 29)^T \cdot 10^6 \cdot psi$ Modulus of Elasticity

$\rho := (145\ \ 490\ \ 490\ \ 490\ \ 490\ \ 490)^T \dfrac{lbf}{ft^3}$ Density

$h := (2.000\ \ 0.0566\ \ 5.8868\ \ 0.0566\ \ 0.300\ \ 0.300)^T \cdot in$ Height

$b := (24.00\ \ 1.625\ \ 0.0566\ \ 1.625\ \ 0.0566\ \ 0.0566)^T \cdot in$ Width

$c := (1.000\ \ 2.0283\ \ 5.000\ \ 7.9717\ \ 2.2066\ \ 7.7934)^T \cdot in$ Location of centroid

$brittle := (1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0)^T$ Brittle? 1=Yes 0=No
(for materials like concrete that cannot carry tension)

$L := 9 \cdot ft$ Span

$DL := 0 \cdot lbf$ Additional weight

$LL := 0 \cdot lbf$ Static load

Section Properties

$$c_g := \frac{\sum \overrightarrow{(E \cdot b \cdot h \cdot c)}}{\sum \overrightarrow{(E \cdot b \cdot h)}}$$

$$
\begin{aligned}
(c_e\ \ H_e\ \ C_e) := \ & H_e \leftarrow h \\
& H_{Last} \leftarrow H_e - h \\
& C_e \leftarrow c \\
& c_e \leftarrow \frac{\sum \overrightarrow{(E \cdot b \cdot h \cdot c)}}{\sum \overrightarrow{(E \cdot b \cdot h)}} \\
& \text{while } \left| \sum H_{Last} - \sum H_e \right| > 5 \cdot 10^{-4} \cdot in \\
& \quad H_{Last} \leftarrow H_e \\
& \quad \text{for } i \in 0..\ rows(h) - 1 \\
& \quad\quad \text{if } brittle_i = 1 \wedge \left| c_e - c_i \right| < \frac{h_i}{2} \\
& \quad\quad\quad H_{e_i} \leftarrow c_e + \frac{h_i}{2} - c_i \\
& \quad\quad\quad C_{e_i} \leftarrow c_e - \frac{H_{e_i}}{2} \\
& \quad\quad \text{if } brittle_i = 1 \wedge c_i - c_e > \frac{h_i}{2} \\
& \quad\quad\quad H_i \leftarrow 0 \\
& \quad\quad\quad C_{e_i} \leftarrow 0 \\
& \quad c_e \leftarrow \frac{\sum \overrightarrow{(E \cdot b \cdot H_e \cdot C_e)}}{\sum \overrightarrow{(E \cdot b \cdot H_e)}} \\
& (c_e\ \ H_e\ \ C_e)
\end{aligned}
$$

$$
\begin{aligned}
(c_p\ \ H_p\ \ C_p) := \ & H_p \leftarrow h \\
& H_{Last} \leftarrow H_p - h \\
& C_p \leftarrow c \\
& c_p \leftarrow \frac{\sum \overrightarrow{(f_y \cdot b \cdot h \cdot c)}}{\sum \overrightarrow{(f_y \cdot b \cdot h)}} \\
& \text{while } \left| \sum H_{Last} - \sum H_p \right| > 5 \cdot 10^{-3} \cdot in \\
& \quad H_{Last} \leftarrow H_p \\
& \quad \text{for } i \in 0..\ rows(h) - 1 \\
& \quad\quad \text{if } brittle_i = 1 \wedge \left| c_p - c_i \right| < \frac{h_i}{2} \\
& \quad\quad\quad H_{p_i} \leftarrow c_p + \frac{h_i}{2} - c_i \\
& \quad\quad\quad C_{p_i} \leftarrow c_p - \frac{H_{p_i}}{2} \\
& \quad\quad \text{if } brittle_i = 1 \wedge c_i - c_p > \frac{h_i}{2} \\
& \quad\quad\quad H_{p_i} \leftarrow 0 \\
& \quad\quad\quad C_{p_i} \leftarrow 0 \\
& \quad c_p \leftarrow \frac{\sum \overrightarrow{(f_y \cdot b \cdot H_p \cdot C_p)}}{\sum \overrightarrow{(f_y \cdot b \cdot H_p)}} \\
& (c_p\ \ H_p\ \ C_p)
\end{aligned}
$$

$c_g = 1.320\,in$ Gross Centroid

$c_e = 1.156\,in$ Cracked Centroid

$c_p = 1.089\,in$ Plastic Centroid

$H_e^T = (1.156\ \ 0.057\ \ 5.887\ \ 0.057\ \ 0.300\ \ 0.300)\,in$

$H_p^T = (1.089\ \ 0.057\ \ 5.887\ \ 0.057\ \ 0.300\ \ 0.300)\,in$

$A := \overrightarrow{b \cdot h}$ $\qquad A^T = (48\ \ 0.092\ \ 0.333\ \ 0.092\ \ 0.017\ \ 0.017)\,in^2$ $\qquad$ Cross sectional areas

$I := \overrightarrow{\frac{b \cdot h^3}{12}}$ $\qquad I^T = (16\ \ 2.455\times10^{-5}\ \ 0.962\ \ 2.455\times10^{-5}\ \ 1.273\times10^{-4}\ \ 1.273\times10^{-4})\,in^4$ $\qquad$ Moments of inertia

$Qe := \overrightarrow{\left(\frac{E}{E_0} \cdot b \cdot He \cdot \left|Ce - ce\right|\right)}$ $\qquad Qe^T = (16.047\ \ 0.608\ \ 9.702\ \ 4.749\ \ 0.135\ \ 0.854)\,in^3$ $\qquad$ Shear Flow

$I_g := \sum \overrightarrow{\frac{E \cdot I}{E_0} + \frac{E \cdot A}{E_0} \cdot (c - c_g)^2}$ $\qquad I_g = 99.061\,in^4$ $\qquad$ Gross moment of inertia

$I_{cr} := \sum \overrightarrow{\frac{E \cdot b \cdot He^3}{12 \cdot E_0} + \frac{E \cdot b \cdot He}{E_0} \cdot (Ce - ce)^2}$ $\qquad I_{cr} = 95.656\,in^4$ $\qquad$ Cracked moment of inertia

$I := \frac{(I_{cr} + I_g)}{2}$ $\qquad I = 97.358\,in^4$ $\qquad$ Effective moment of inertia

$M_e := \min\left(\overrightarrow{\frac{E_0 \cdot I_{cr}}{E} \frac{f_y}{\left|Ce - ce\right| + \frac{He}{2}}}\right)$ $\qquad M_e = 7.306\times10^4\,in \cdot lbf$ $\qquad$ Elastic Moment Capacity

$$
\begin{aligned}
M_p := \;& M \leftarrow 0 \cdot in \cdot lbf \\
& \text{for } j \in 0 .. \text{rows}(h) - 1 \\
& \quad \left[M \leftarrow M + \left[f_{y_j} \cdot \left(H_{p_j} \cdot b_j\right) \cdot \left(C_{p_j} - c_p\right)\right]\right] \text{ if } \left(C_{p_j} - \frac{H_{p_j}}{2}\right) > c_p \\
& \quad \left[M \leftarrow M + \left[f_{y_j} \cdot \left(H_{p_j} \cdot b_j\right) \cdot \left(c_p - C_{p_j}\right)\right]\right] \text{ if } \left(C_{p_j} + \frac{H_{p_j}}{2}\right) < c_p \\
& \quad \left[M \leftarrow M + f_{y_j} \cdot \left(H_{p_j} \cdot b_j\right) \cdot \left[\frac{\left(H_{p_j}\right)^2 + 4\left(C_{p_j}\right)^2 - 8 \cdot C_{p_j} \cdot c_p + 4 \cdot c_p^2}{4 \cdot H_{p_j}}\right]\right] \text{ otherwise} \\
& M
\end{aligned}
$$

$M_p = 1.707\times10^5\,in \cdot lbf$ $\qquad$ Plastic Moment Capacity

Beam Properties

$m_t := \dfrac{\sum \left(\overrightarrow{A \cdot L \cdot \rho}\right)}{g} + \dfrac{DL}{g}$	$m_t = 1170399 \dfrac{lbf \cdot (msec)^2}{in}$	Total mass
$k_E := \dfrac{384 \cdot E_0 \cdot I}{5 \cdot L^3}$	$k_E = 2.272 \times 10^4 \dfrac{lbf}{in}$	Elastic spring rate
$R_m := \dfrac{8 \cdot M_p}{L}$	$R_m = 1.265 \times 10^4 \, lbf$	Maximum elastic resistance
$y_{el} := \dfrac{R_m}{k_E}$	$y_{el} = 0.557 \, in$	Elastic yield displacement
$F_{in} := LL$	$F_{in} = 0 \, lbf$	Initial gravity load
$R_{adj} := R_m - F_{in}$	$R_{adj} = 1.265 \times 10^4 \, lbf$	Resistance adjusted for gravity
$y_{adj} := \dfrac{R_{adj}}{k_E}$	$y_{adj} = 0.557 \, in$	Yield displacement adjusted for gravity
$K_{LM_0} := .78$	$K_{LM_1} := .66$	Transformation factors
$T := 2 \cdot \pi \cdot \sqrt{\dfrac{K_{LM_0} \cdot m_t}{k_E}}$	$T = 39.827 \, msec$	Natural period
$c_{cr} := 2 \cdot \sqrt{k_E \cdot K_{LM_0} \cdot m_t}$	$c_{cr} = 2.88 \times 10^5 \dfrac{lbf \cdot msec}{in}$	Critical damping coefficient
$M := K_{LM_1} \cdot m_t$	$M = 7.72463 \times 10^5 \dfrac{lbf \cdot (msec)^2}{in}$	Effective mass per unit area

SDOF Parameters

$K_E := k_E \cdot \frac{in}{lbf}$ $\qquad K_E = 2.272 \times 10^4$ $\qquad$ Elastic spring rate

$R_m := R_m \cdot \frac{1}{lbf}$ $\qquad R_m = 1.265 \times 10^4$ $\qquad$ Maximum resistance

$F_{in} := F_{in} \cdot \frac{1}{lbf}$ $\qquad F_{in} = 0$ $\qquad$ Initial gravity load

$c_{cr} := c_{cr} \cdot \left(\frac{in}{lbf \cdot msec}\right)$ $\qquad c_{cr} = 2.88 \times 10^5$ $\qquad$ Critical damping coefficient

$y_{el} := y_{el} \cdot \frac{1}{in}$ $\qquad y_{el} = 0.557$ $\qquad$ Elastic yield displacement

$y_{in} := \frac{F_{in}}{K_E}$ $\qquad y_{in} = 0$ $\qquad$ Initial displacement

$$K_{LM}(y_1, y_2) := \begin{cases} K_{LM_0} & \text{if } |y_1 - y_2| \le y_{el} \\ K_{LM_1} & \text{otherwise} \end{cases}$$

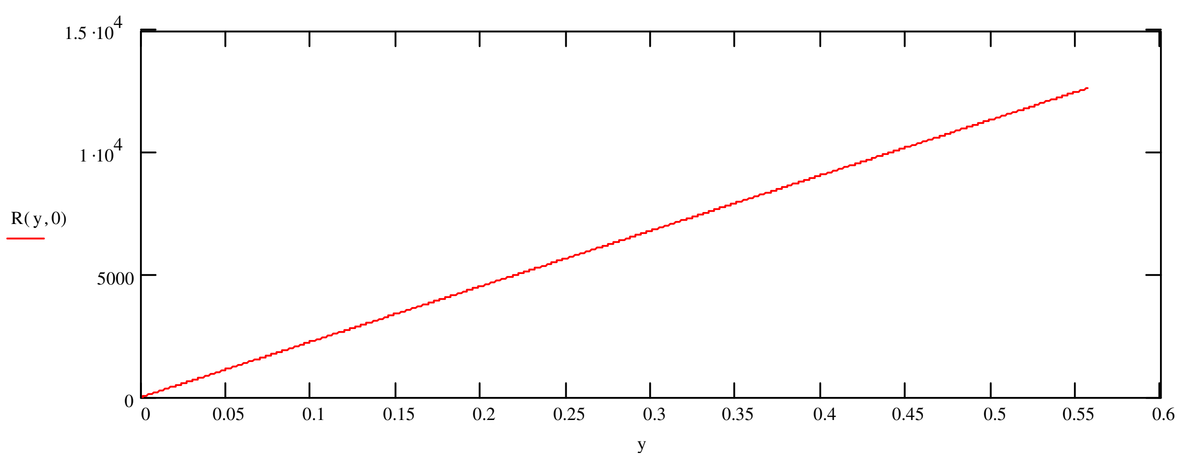
$K_{LM}(0,0) = 0.78$ $\qquad$ Transformation Factor

$$M(y_1, y_2) := K_{LM}(y_1, y_2) \cdot \frac{m_t}{\frac{lbf \cdot (msec)^2}{in}}$$

$M(0,0) = 9.12911 \times 10^5$ $\qquad$ Effective mass

Resistance Function

$R(y_1, y_2) := K_E \cdot (y_1 - y_2)$ $\qquad y := 0, \frac{y_{el}}{1000} .. y_{el}$



SDOF Calculations

$N := 2000$ Number of time steps

$dur := 200$ Calculation time (msec)

$$y := \begin{pmatrix} 0 \\ 0 \\ -y_{in} \end{pmatrix}$$ Initial values

$$D_1(t,y) := \begin{bmatrix} y_1 \\ \frac{1}{M(y_0, y_2)} \cdot \left(F(t) + F_{in} - R(y_0, y_2) - 0.0002 \cdot c_{cr} \cdot y_1\right) \\ \begin{cases} y_1 & \text{if } \left[(y_0 - y_2) > y_{el}\right] \cdot (y_1 > 0) \\ y_1 & \text{if } \left[(y_0 - y_2) < -y_{el}\right] \cdot (y_1 < 0) \\ 0 & \text{otherwise} \end{cases} \end{bmatrix}$$

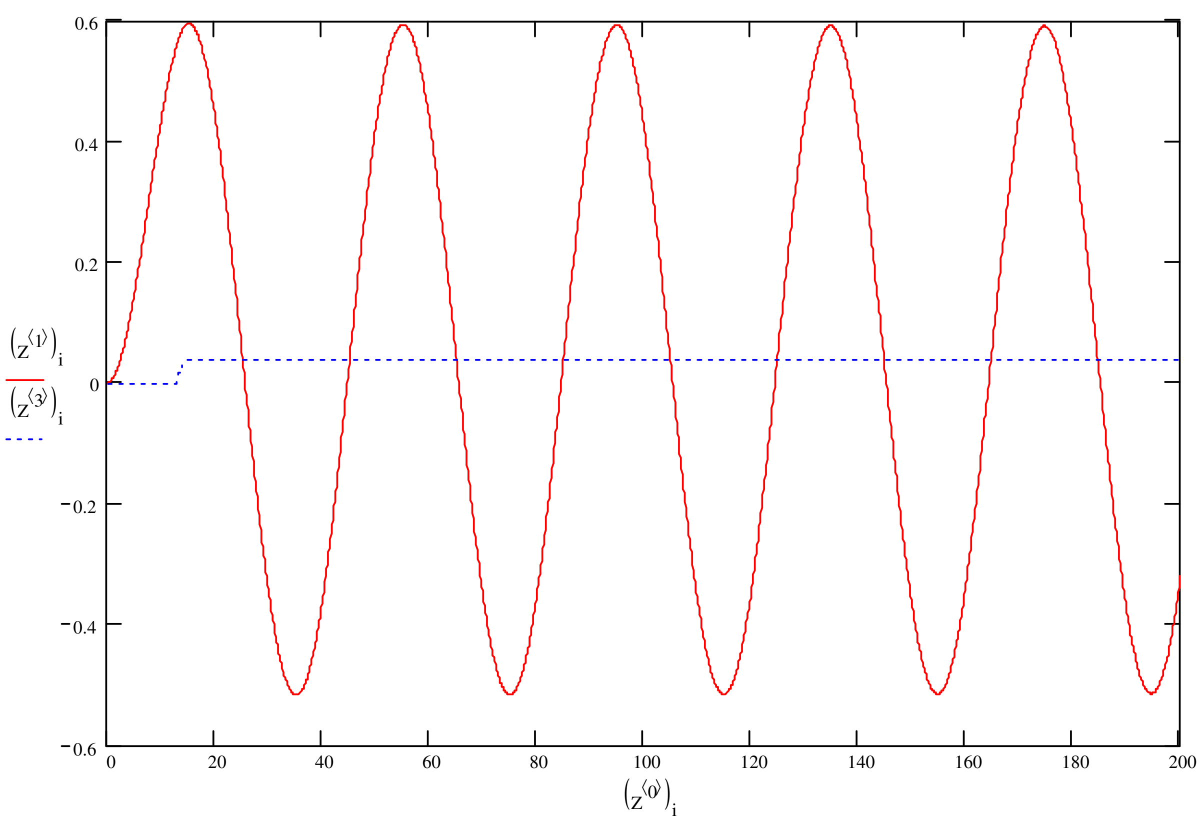
System of first order differential equations

$Z := \text{rkfixed}(y, 0, dur, N, D_1)$ $i := 0 .. N$

$y_m := \max\left(Z^{\langle 1 \rangle}\right)$ $y_m = 0.5949$ Maximum displacement

$\mu_y := \frac{y_m + y_{in}}{y_{el}}$ $\mu_y = 1.069$ Ductility

$\theta := \text{atan}\left(\frac{2 \cdot y_m \cdot in}{L}\right)$ $\theta = 0.631\,deg$ Rotation



Maximum Response Calculations

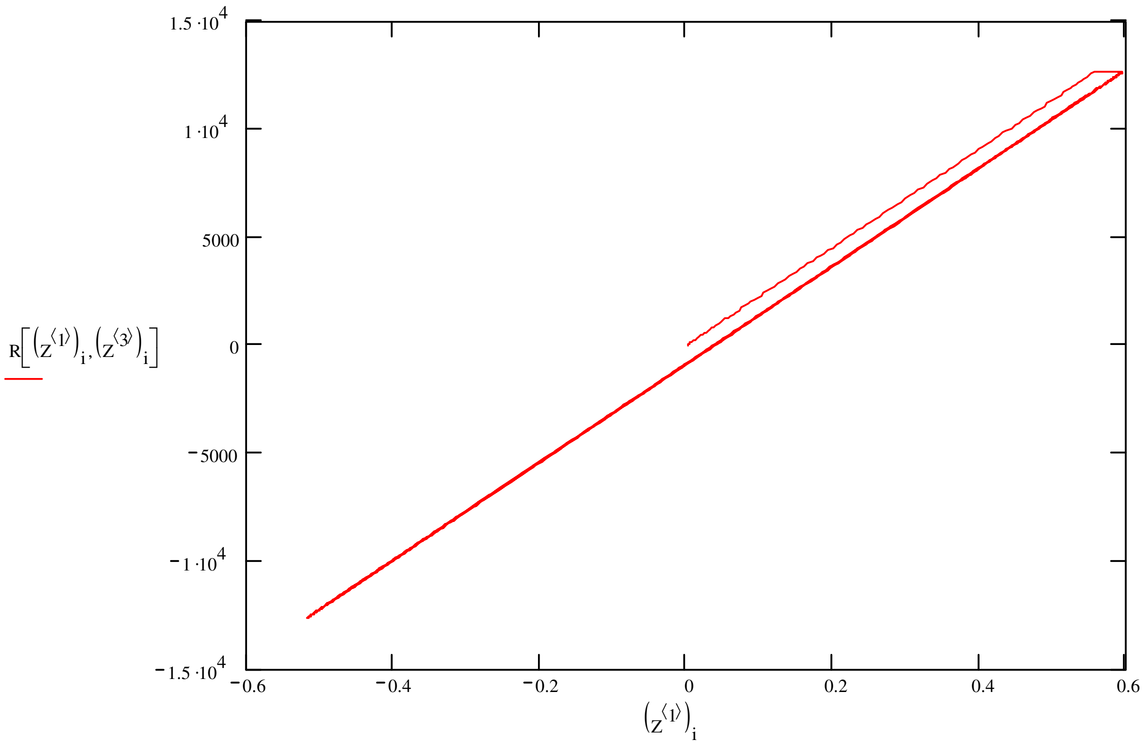
$$n := \begin{array}{|l} y_{max} \leftarrow 0 \\ \text{for } i \in 1..N \\ \quad \text{if } \left(Z^{\langle 1 \rangle}\right)_i > y_{max} \\ \quad\quad \begin{array}{|l} y_{max} \leftarrow \left(Z^{\langle 1 \rangle}\right)_i \\ t_{max} \leftarrow \left(Z^{\langle 0 \rangle}\right)_i \\ n \leftarrow i \end{array} \\ n \end{array}$$

$n = 152$ — Time step of max response

$t_{max} := \left(Z^{\langle 0 \rangle}\right)_n$ $\quad t_{max} = 15.200$ — Time of max. response

$F(t_{max}) = 1.466 \times 10^3$ — Force at time of max response

$y_{plastic} := \left(Z^{\langle 3 \rangle}\right)_n + y_{in}$ $\quad y_{plastic} = 0.038$ — Maximum plastic deformation



Calculate Reaction Loads

$$R_f(i) := \begin{cases} 0.39 & \text{if } \left|R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right]\right| < R_m \\ 0.38 & \text{otherwise} \end{cases}$$

$R_f(n) = 0.38$

$$F_f(i) := \begin{cases} 0.11 & \text{if } \left|R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right]\right| < R_m \\ 0.12 & \text{otherwise} \end{cases}$$

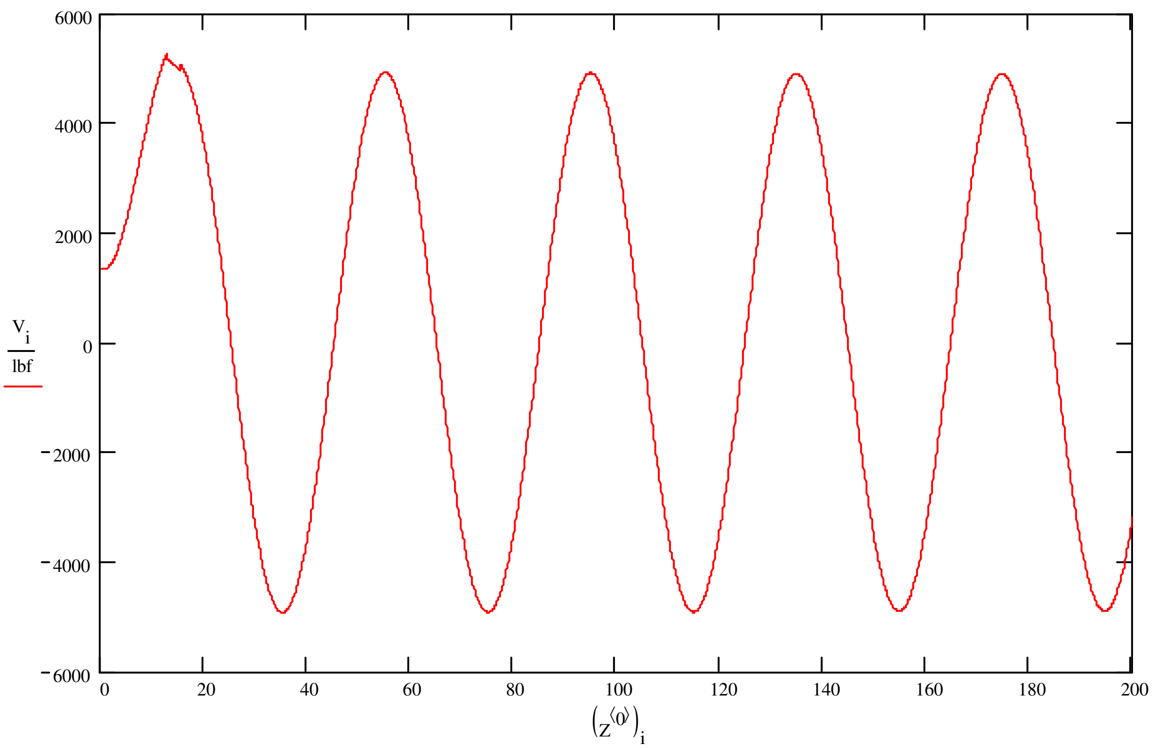
$F_f(n) = 0.12$

$$V_i := \left[R_f(i) \cdot R\left[\left(Z^{\langle 1\rangle}\right)_i, \left(Z^{\langle 3\rangle}\right)_i\right] + F_f(i) \cdot \left[F\left[\left(Z^{\langle 0\rangle}\right)_i\right] + F_{in}\right]\right] \cdot \text{lbf}$$

$V_n = 4983\,\text{lbf}$ Shear at time of max response (includes gravity loads)

$V_n - \frac{F_{in} \cdot \text{lbf}}{2} = 4983\,\text{lbf}$ Shear at time of max response (without gravity loads)

$\max(V) = 5270\,\text{lbf}$



$$\frac{V_n \cdot Q_e}{I_g} = \begin{pmatrix} 807.266 \\ 30.562 \\ 488.067 \\ 238.891 \\ 6.796 \\ 42.949 \end{pmatrix} \frac{\text{lbf}}{\text{in}}$$

Shear flow between sections

Check Weld of Legs To Base Plate For Anchor

Shear Force Per Leg: $V_{per} := \max(V)$ $V_{per} = 5270\,\text{lbf}$

Determine Required Weld Length and Spacing

Using 1/8" Fillet Weld with E70xx Electrode

E 70xx Electrode Strength: $f_y := 70000\,\text{psi}$

Nominal Leg Length of Welds: $a := \frac{1}{8}\text{in}$

Effective Throat: $t_e := \min(0.707 \cdot a, .0566 \cdot \text{in})$ $t_e = 0.057\,\text{in}$

Weld Strength per Inch: $S_{weld} := 0.40 \cdot f_y$ $S_{weld} = 28000\,\text{psi}$

Use a Minimum of 4 inch Long Welds : $WL := 4\text{in}$

Stress Due to Shear: $f_v := \frac{V_{per}}{t_e \cdot WL}$ $f_v = 23277\,\text{psi}$

Factor of Safety For Weld of Baseplate to Steel At Head: $FS := \frac{S_{weld}}{f_v}$ $\boxed{FS = 1.203}$

```
Single Degree Of Freedom (SDOF)
 Version 2.0 - Release April 2006
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 Time = 15:10:16.265

 Studs CW I

                  METAL BEAM SDOF ANALYSIS

   Boundary Condition for Beam                            =       simple
   Load Condition for Beam                                = uniform load
   Desired Response                                       =      plastic
   Load-Mass Factor                                       =         0.66
   Resistance Factors
         Midspan                                          =         8.00
   Stiffness Factor                                       =        76.80
   Span, in                                               =       108.00
   Additional Mass, lbf                                   =       435.00
   Additional Static Load, lbf                            =         0.00

                 CROSS SECTION MATERIALS

   -------------------------------------------------------------
    Material           | Young's | Mass     |  Yield  | Strength
    Name               | Modulus | Density |  Stress | Increase
                       |  (ksi)  |  (pcf)  |  (ksi)  | Factor
   -------------------------------------------------------------
   Steel A572 Grade 50 |   29000 |     490 |      50 |      1.2
   -------------------------------------------------------------

                 CROSS SECTION DEFINITION

   ---------------------------------------------------------------------
    Element |  Width |  Depth |   X'   |   Y'   |         Material
    ID      |   (in) |   (in) |  (in)  |  (in)  |            ID
   ---------------------------------------------------------------------
          0 |  1.625 |  0.057 |      0 |      3 |    Steel A572 Grade 50
          1 |  0.057 |  5.887 | -0.784 |      0 |    Steel A572 Grade 50
          2 |  1.625 |  0.057 |      0 |     -3 |    Steel A572 Grade 50
          3 |  0.057 |    0.3 |  0.784 |  -2.85 |    Steel A572 Grade 50
          4 |  0.057 |    0.3 |  0.784 |   2.85 |    Steel A572 Grade 50
   ---------------------------------------------------------------------

                 CROSS SECTION PROPERTIES

   Area, in^2                                             =         0.55
   Weight, lbf/ft                                         =         1.88
   Moment of Inertia, in^4                                =          2.9
   Elastic Section Modulus, in^3                          =         0.96
   Plastic Section Modulus, in^3                          =         1.14


                 CALCULATED PROPERTIES

   Total Mass, lbf*msec^2/in                              =   1169600.60
   Effective Mass, lbf*msec^2/in                          =    771936.40
   Maximum moment, in-lbf                                 =     68497.70
   Section Resistance, lbf                                =      5073.90
   Section Stiffness, lbf/in                              =      5127.27
   Yield Deflection, in                                   =         0.99
   Natural Period, msec                                   =        77.10

        RESISTANCE FUNCTION                LOADING FUNCTION
         (lbf)        (in)               (msec)       (lbf)
          0.00        0.00
       5073.90        0.99
       5073.90      989.59
```

SDOF PARAMETERS

Critical Damping Ratio, %	=	0.200
Time Step, msec	=	0.154

SDOF RESULTS

Time of Yield, msec	=	13.88
Ductility	=	1.803
Rotation	=	1.893
Peak Dynamic Shear, lbf	=	2218.29

		MAXIMUMS		MINIMUMS	
		Value	Time	Value	Time
ACC	=	0.1600E-01	0.0000E+00	-0.6599E-02	0.1727E+02
VEL	=	0.1010E+00	0.1172E+02	-0.8040E-01	0.4872E+02
DISP	=	0.1784E+01	0.2945E+02	-0.1886E+00	0.6800E+02

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Single Degree Of Freedom (SDOF)
 Version 2.0 - Release April 2006
 Date = 06/25/2010
 Time = 15:10:16.483

 Studs CW II

                 METAL BEAM SDOF ANALYSIS

   Boundary Condition for Beam                            =       simple
   Load Condition for Beam                                = uniform load
   Desired Response                                       =      elastic
   Load-Mass Factor                                       =         0.78
   Resistance Factors
         Midspan                                          =         8.00
   Stiffness Factor                                       =        76.80
   Span, in                                               =       108.00
   Additional Mass, lbf                                   =       435.00
   Additional Static Load, lbf                            =         0.00

                CROSS SECTION MATERIALS

   -------------------------------------------------------------
    Material           | Young's | Mass    |  Yield  | Strength
    Name               | Modulus | Density |  Stress | Increase
                       |  (ksi)  |  (pcf)  |  (ksi)  | Factor
   -------------------------------------------------------------
    Steel Stud (33ksi) |   29000 |     490 |      33 |      1.2
   -------------------------------------------------------------

                CROSS SECTION DEFINITION

   ---------------------------------------------------------------------
    Element |  Width |  Depth |   X'   |   Y'   |        Material
    ID      |   (in) |   (in) |  (in)  |  (in)  |           ID
   ---------------------------------------------------------------------
          0 |  1.625 |  0.057 |      0 |      3 |     Steel Stud (33ksi)
          1 |  0.057 |  5.887 | -0.784 |      0 |     Steel Stud (33ksi)
          2 |  1.625 |  0.057 |      0 |     -3 |     Steel Stud (33ksi)
          3 |  0.057 |    0.3 |  0.784 |  -2.85 |     Steel Stud (33ksi)
          4 |  0.057 |    0.3 |  0.784 |   2.85 |     Steel Stud (33ksi)
   ---------------------------------------------------------------------

                CROSS SECTION PROPERTIES

   Area, in^2                                             =         0.55
   Weight, lbf/ft                                         =         1.88
   Moment of Inertia, in^4                                =          2.9
   Elastic Section Modulus, in^3                          =         0.96
   Plastic Section Modulus, in^3                          =         1.14


                CALCULATED PROPERTIES

   Total Mass, lbf*msec^2/in                              =   1169600.60
   Effective Mass, lbf*msec^2/in                          =    913750.47
   Maximum moment, in-lbf                                 =     45208.48
   Section Resistance, lbf                                =      3348.78
   Section Stiffness, lbf/in                              =      5127.27
   Yield Deflection, in                                   =         0.65
   Natural Period, msec                                   =        83.88

        RESISTANCE FUNCTION                 LOADING FUNCTION
          (lbf)        (in)                (msec)       (lbf)
           0.00        0.00
        3348.78        0.65
        3348.78      653.13
```

SDOF PARAMETERS

Critical Damping Ratio, %	=	0.200
Time Step, msec	=	0.168

SDOF RESULTS

Time of Yield, msec	=	11.91
Ductility	=	1.924
Rotation	=	1.333
Peak Dynamic Shear, lbf	=	1618.82

		MAXIMUMS		MINIMUMS	
		Value	Time	Value	Time
ACC	=	0.1637E-01	0.0000E+00	-0.3685E-02	0.1191E+02
VEL	=	0.7432E-01	0.8723E+01	-0.4877E-01	0.5100E+02
DISP	=	0.1257E+01	0.3003E+02	-0.4557E-01	0.7197E+02

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Single Degree Of Freedom (SDOF)
 Version 2.0 - Release April 2006
 Date = 06/08/2010
 Time = 16:58:07.665

 Track CW II

                  METAL BEAM SDOF ANALYSIS

   Boundary Condition for Beam                            =        fixed
   Load Condition for Beam                                =   point load
   Desired Response                                       =      elastic
   Load-Mass Factor                                       =         0.37
   Resistance Factors
         Midspan                                          =         4.00
         Edge                                             =         4.00
   Stiffness Factor                                       =       192.00
   Span, in                                               =        48.00
   Additional Mass, lbf                                   =       226.00
   Additional Static Load, lbf                            =         0.00

                 CROSS SECTION MATERIALS

   -------------------------------------------------------------
    Material           | Young's | Mass    |  Yield  | Strength
    Name               | Modulus | Density |  Stress | Increase
                       |  (ksi)  |  (pcf)  |  (ksi)  | Factor
   -------------------------------------------------------------
    Steel Stud (33ksi) |   29000 |     490 |      33 |      1.2
   -------------------------------------------------------------

                 CROSS SECTION DEFINITION

   ---------------------------------------------------------------------
    Element |  Width |  Depth |   X'   |  Y'   |        Material
    ID      |   (in) |   (in) |  (in)  |  (in) |           ID
   ---------------------------------------------------------------------
          0 |  1.255 |  0.072 |      0 |  2.78 |     Steel Stud (33ksi)
          1 |  0.072 |   5.42 | -0.589 |     0 |     Steel Stud (33ksi)
          2 |  1.255 |  0.072 |      0 | -2.78 |     Steel Stud (33ksi)
   ---------------------------------------------------------------------

                 CROSS SECTION PROPERTIES

   Area, in^2                                             =         0.57
   Weight, lbf/ft                                         =         1.94
   Moment of Inertia, in^4                                =         2.35
   Elastic Section Modulus, in^3                          =         0.84
   Plastic Section Modulus, in^3                          =         1.03


                 CALCULATED PROPERTIES

   Total Mass, lbf*msec^2/in                              =    604985.17
   Effective Mass, lbf*msec^2/in                          =    223844.51
   Maximum moment, in-lbf                                 =     40834.60
   Section Resistance, lbf                                =      6805.77
   Section Stiffness, lbf/in                              =    118315.97
   Yield Deflection, in                                   =         0.06
   Natural Period, msec                                   =         8.64

        RESISTANCE FUNCTION               LOADING FUNCTION- CWII
         (lbf)        (in)
          0.00        0.00
       6805.77        0.06
       6805.77       57.52
```

```
                SDOF PARAMETERS
  Critical Damping Ratio, %                                    =        0.200
  Time Step, msec                                              =        0.017

                 SDOF RESULTS
  Ductility                                                    =        0.969
  Rotation                                                     =        0.133
  Peak Dynamic Shear, lbf                                      =      4582.26

              MAXIMUMS                         MINIMUMS
           Value       Time                 Value       Time
ACC  =    0.2517E-01  0.9161E+01        -0.2733E-01  0.4010E+01
VEL  =    0.2735E-01  0.1051E+02        -0.2689E-01  0.4121E+02
DISP =    0.5575E-01  0.4045E+01        -0.3220E-01  0.1706E+02
```