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# Evaluation of NEHRP Guidelines for the Seismic Rehabilitation of the McChord Air Force Base Fire Station

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## ABSTRACT

This paper evaluates FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, in regard to design, construction costs, and general engineering practice. Three methodologies are compared: (1) FEMA 178, current seismic rehabilitation design practice (referred to as "Prevailing Practice"), (2) FEMA 273 Basic Safety Objective (BSO), and (3) FEMA 273 Immediate Occupancy (IO). The McChord AFB Fire Station provides the analytical model. The model structure is a Type 2 wood building industrial facility (as defined by FEMA), constructed of wood stud walls with flexible wood diaphragms and plywood or diagonally-sheathed shear walls. Primary areas of inadequate strength and/or ductility are identified as well as proposed rehabilitation and resulting costs using the three methodologies.

Based on the model design, FEMA 273 *Guidelines* produce significantly greater design and construction costs than prevailing practice. *Guideline* design costs are approximately 40 percent higher than prevailing practice due to increased analysis requirements and a greater amount of rehabilitation design. BSO design requires considerably more rehabilitation than prevailing practice design, and IO design requires more rehabilitation than the BSO design. BSO construction cost estimates are more than three times greater than prevailing practice, and enhancing the rehabilitation objective design from BSO to IO results in a 23 percent increase in construction cost. FEMA 273 *Guidelines* appear to be rational, detailed, and consistent with good engineering practice; however, this paper identifies several inconsistent, ambiguous, or contradictory provisions and recommends areas of additional research.

## INTRODUCTION

The newly published *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 273) and its associated *Commentary* (FEMA 274) provides criteria for the seismic rehabilitation of existing structures. The FEMA 273 document provides uniform criteria by which existing buildings may be rehabilitated to attain a range of different performance levels when subjected to earthquakes of varying severity. This approach is unique and unlike that adopted presently by building codes for new construction where building performance is implicit and not obvious to the user. As part of a case studies project performed for the Building Seismic Safety Council (BSSC) to evaluate the *Guidelines*, several different seismic rehabilitation designs were prepared in accordance with the following: (1) Prevailing Practice (FEMA 178 force levels), (2) FEMA 273 Basic Safety Objective, and (3) FEMA 273 Immediate Occupancy. In Washington State, a current method used for seismic rehabilitation of existing buildings is FEMA 178 (*NEHRP Handbook for the Seismic Evaluation of Existing Buildings*) combined with selected provisions of the Uniform Building Code. These criteria are used in this evaluation as "Prevailing Practice" to comparatively determine the *Guideline's* impact on design and construction costs for seismic rehabilitation.

## NARRATIVE DESCRIPTION

### Building Function and Overview

The McChord AFB Fire Station houses fire fighting personnel and equipment for responding to aircraft crashes and building fires. The fire station is considered an essential facility and is the only fire fighting facility on McChord AFB. The overall dimensions are approximately 209 feet by 121 feet; the floor area is approximately 22,000 square

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feet. Constructed originally in 1951, the building has five subsequent additions. The original building, approximately 14,500 square feet, contains a one-story high bay vehicle space, one-story office/sleeping quarters space, two-story office/training rooms, and a five-story hose drying tower. In 1963, a 640 square foot $CO_2$ room was added at the north end of the building. In 1979, a 3,900 square foot high bay area was constructed at the north end of the building resulting in three vehicle bays. In 1983, an 800 square foot office was added at the northwest end of the facility. In 1990, a 1,100 square foot television and weight room was constructed at the southeast end of the building. In 1998, an 840 square foot one-story office space was added along the west side of the fire station.

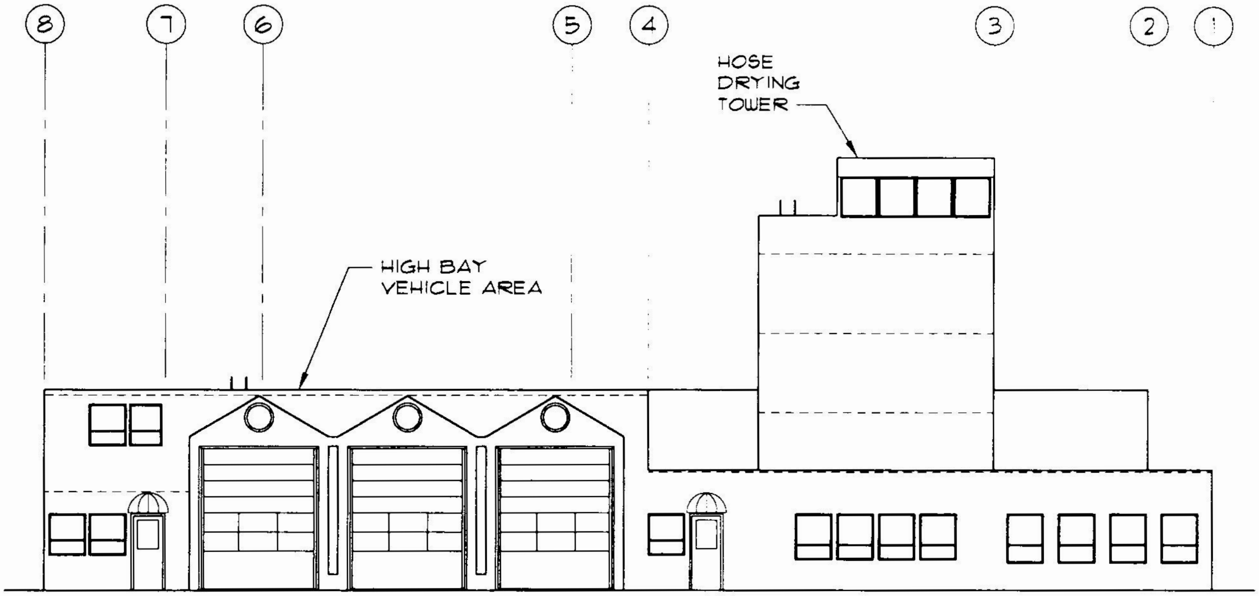

Figure 1. South Elevation Fire Station

## Existing Building Framing System

FEMA defines the McChord AFB Fire Station as a Type 2 Wood Building Industrial Facility. Building construction consists of wood stud wall framing sheathed with either 3/4-inch diagonal sheathing (original construction) or 1/2-inch plywood (later construction). Roof framing is primarily metal bar joists supporting wood decking (either straight or diagonal) or plywood decking. Lateral forces are resisted by plywood or diagonally sheathed flexible diaphragms and wood shear walls. Ground floor construction is slab-on-grade in all areas. The Fire Station is divided into four main building areas for purposes of analysis and retrofit design: (1) high bay areas, (2) one-story offices and sleeping quarters, (3) two-story training rooms and offices, and (4) five-story hose drying tower.

## Analytical Model

Given the complex configuration of the building and the relatively simple nature of modeling wood buildings with flexible wood diaphragms, hand calculation methods are used for the seismic analysis of the structure. The building has 11 discrete floor and roof diaphragms that distribute the seismic base shear to the shear walls. For the purposes of computing the total seismic base shear, the shear forces from the five-story tower are computed separately from the main building. The drying tower base is assumed to be transferred into the main building lateral system at the main building roof level. Seismic forces are assumed to act uniformly over floor and roof diaphragms and are distributed to shear walls in accordance with tributary areas. This method of distributing seismic load to shear walls is commonly used in the analysis of wood buildings with flexible wood diaphragms. Floor and roof diaphragm stresses and chord forces, shear wall unit stresses, and overturning are checked against allowable values.

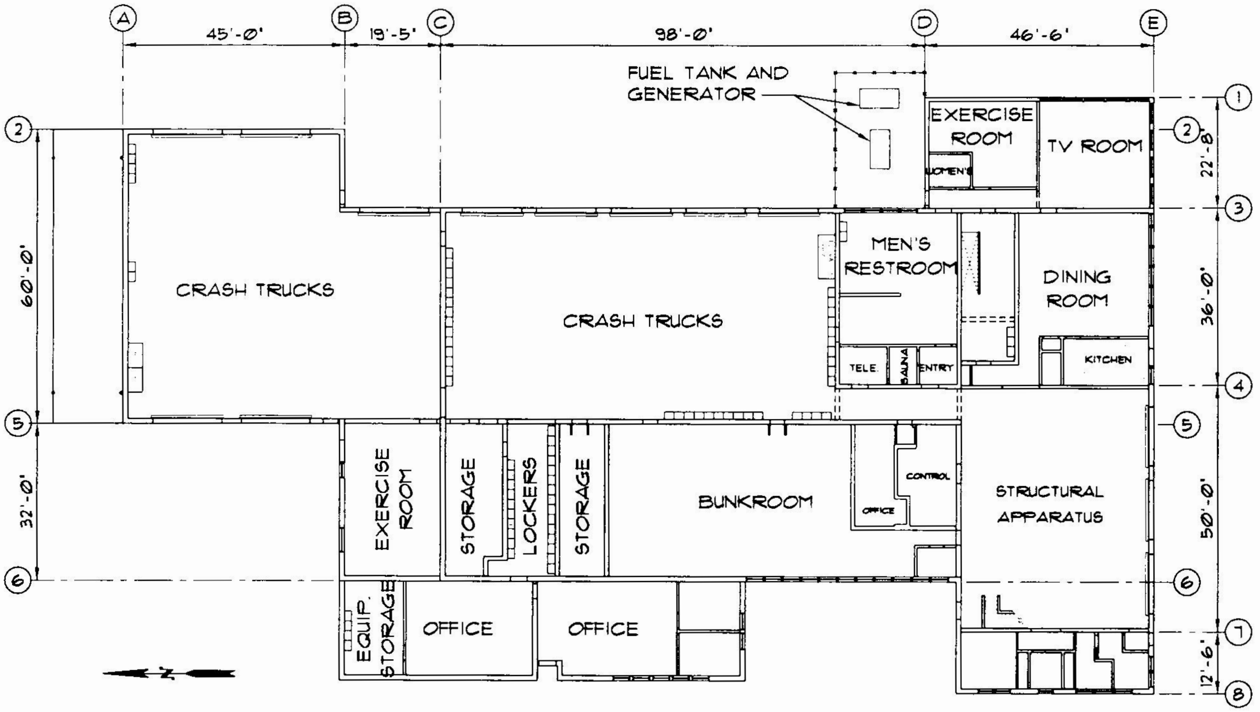

Figure 2. First Floor Plan, Fire Station

The building foundation, including shallow spread footings and slabs-on-grade, are evaluated for both soil bearing, sliding friction, and development of passive pressure. The stiffness of the concrete foundations is typically much greater for buildings of this type than the stiffness of the lightly loaded wood building elements, and the foundation is assumed to be infinitely rigid relative to the building framing. Due to insufficient data, Site Class D is assumed in determining spectral response parameters for the BSE-1 and BSE-2 ground motions. Soil Type $S_3$ is assumed in determining the base shear for the prevailing practice design. A 5 percent damped response spectrum is assumed for determining the damping coefficients in accordance with the *Guidelines*.

## REHABILITATION DESIGN COMPARISON

### Design Forces

The design base shear forces summarized in Table 1 provide a comparison of the different force levels employed in the different design procedures. The FEMA 273 force levels are pseudo lateral forces intended to impose inelastic displacement compatibility with an elastic analysis. For force-controlled elements, where load is not limited by a "weak link," the force level is used to define a yield limit state. Basic Safety Earthquake 1 (BSE-1) forces correspond to a 2 percent/50-year event; BSE-2 forces correspond to a 10 percent/50-year event. The FEMA 178 (Prevailing Practice) force levels are reduced forces assuming non-linear structural response.

BSE-2 forces at the collapse prevention level control the design of all elements and components in the BSO design. At the IO performance level, BSE-2 force levels control the design for force-controlled elements; however, BSE-1 forces control the design for deformation-controlled elements due to the reduced ductility (*m*) factors for this performance category.

Table 1. Design Base Shear Summary

| Building | Prevailing Practice Design (FEMA 178) | Basic Safety Objective Design (FEMA 273) | | Immediate Occupancy Design (FEMA 273) | |
|---|---|---|---|---|---|
| | | BSE-1 Life Safety | BSE-2 Collapse Prev. | BSE-1 Immed. Occ. | BSE-2 Collapse Prev. |
| Tower | 5 kips | 26 kips | ^* 41 kips | * 26 kips | ^ 41 kips |
| Main Building | 87 kips | 564 kips | ^* 968 kips | *564 kips | ^ 968 kips |
| Total | 92 kips | 590 kips | ^*1009 kips | *590 kips | ^1009 kips |

Notes: ^ Controlled for force controlled elements.
* Controlled for deformation controlled elements.

Diaphragms

All roof and floor diaphragms are determined to have adequate strength under the prevailing practice analysis. For the designs employing the *Guidelines*, all straight and diagonally sheathed diaphragms require strengthening due to the small recommended strength and ductility ($m$) factors. This results in a dramatic cost impact, because the existing floor and built-up roofing materials need to be removed to install plywood sheathing. All existing plywood diaphragms are evaluated and found to be adequate under the *Guidelines'* provisions.

Shear Walls and Frames

The seismic demand for the various wood shear wall elements for this building is summarized by the use of demand/capacity ratios (DCRs). These ratios allow for the rapid evaluation of the various lateral load resisting elements to determine the critically overstressed elements requiring seismic strengthening and stiffening. Table 2 summarizes the number of walls determined to be overstressed (DCR > 1.0) at the different rehabilitation levels. In general, most shear walls under prevailing practice design have DCRs below 1.0 except for the highly loaded shear walls opposite the high bay vehicle doors. Under *FEMA 273 Guidelines*, the number of overstressed shear walls increases dramatically, since the "demand" increases by a greater factor than the "capacity." The force level (i.e., demand) for the BSO design is approximately 11 times greater than the forces used for the prevailing practice design; however, the 1,750 plf capacity ($m\kappa Q_{CE}$) for single, diagonally sheathed shear walls used for the BSO design is only six times greater than the 300 plf shear strength value used for prevailing practice design.

Table 2. Shear Wall Demand/Capacity Ratio (DCR) Summary

| Rehabilitation Objective | North-South Direction (30 walls total) Number of Walls with DCR > 1.0 | East-West Direction (21 walls total) Number of Walls with DCR > 1.0 |
|---|---|---|
| Prevailing Practice | 5 (17%) | 7 (33%) |
| BSE-1, Life Safety (BSO) | 7 (24%) | 8 (38%) |
| BSE-2, Collapse Prevention (BSO, IO) | 16 (55%) | 16 (76%) |
| BSE-1, Immediate Occupancy (IO) | 23 (79%) | 17 (81%) |

The limitation on shear wall height to length (h/L) ratios also affects the building evaluation. *FEMA 273 Guidelines'* upper limit on shear wall height to length (h/L) ratios is considerably less than allowed by prevailing practice. Prevailing practice limits h/L ratios for diagonal sheathing to 2:1 (UBC Table 23-I-I), compared to *FEMA 273 Guidelines* (Table 8-2) values of 1.5:1. Limiting h/L values for plywood shear walls for both prevailing practice and FEMA 273 is the same at 3.5:1. Due to the more restrictive h/L limits for the BSO design, certain walls (e.g., in the hose drying tower) no longer qualify as shear walls. Therefore, window openings in the hose drying tower will be in-filled with wood framing and plywood sheathing to improve the h/L ratios and overall shear capacity.

Foundations

The existing slab-on-grade adjacent to the high bay roll-up doors is inadequate to resist the column reactions from the proposed moment frames for both the prevailing practice and FEMA 273 designs; therefore, concrete grade beams adjacent to the existing continuous footings are required for all design methods. The columns of the proposed braced frames used for the *FEMA 273 Guidelines'* design are subject to significant uplift forces that are unable to be resisted by the dead load of a reasonably sized concrete footing. Foundation helical anchors integrated with square concrete footings are required for all braced frame foundations to resist the overturning forces.

### Structural Improvements

The results of the evaluation comparing prevailing practice and FEMA 273 designs indicates the existing building possesses inadequate lateral strength, ductility, and continuity. The following are proposed to correct or strengthen theses deficiencies:

1. Install structural steel moment frames and concrete grade beams along the large high bay roll-up door openings.
2. Install structural steel braced frames with spread footings and helical soil anchors to resist shear and frame uplift forces in the high bay areas.
3. Install shear collectors/struts to transfer diaphragm shear forces to steel frames or strengthened wood shear walls.
4. In-fill existing window openings with wood studs and plywood sheathing to improve shear wall capacity.
5. Install plywood sheathing to strengthen and stiffen existing diagonally sheathed shear walls.
6. Install shear wall holddown straps and anchors to resist shear wall overturning forces.
7. Install plywood sheathing over the diagonally sheathed roof and floor diaphragms.

Table 3. Number of Required Seismic Rehabilitation Elements

| Description of Proposed Rehabilitation Elements | Prevailing Practice | Basic Safety Objective (BSO) | Immediate Occupancy (IO) |
|---|---|---|---|
| Number of moment frames along high bay roll-up doors | 2 | 2 | 2 |
| Number of braced frames adjacent to existing walls | 0 | 4 | 6 |
| Number of in-fill window openings | 2 | 13 | 17 |
| Number of strengthened shear walls | 4 | 11 | 9 |
| Number of strengthened roof/floor diaphragms | 0 | 10 | 10 |

As depicted in Table 3, considerable rehabilitation is required for the BSO design compared to design by prevailing practice. Steel braced frames and diaphragm overlays are required in the BSO design but not in prevailing practice. In addition, the BSO design requires 11 more window openings to be in-filled and 7 more shear walls to be strengthened than required under prevailing practice. Enhancing the *FEMA 273 Guidelines'* objective from BSO to IO requires installation of two additional steel-braced frames and in-filling four additional window openings.

### Rehabilitation Costs

The estimated construction cost for the BSO design is more than three times greater than the estimated construction cost for prevailing practice. The BSO design requires a significantly greater amount of rehabilitation than required for the prevailing practice design. The largest cost component associated with the BSO design is due to the strengthening of diaphragms and installation of steel-braced frames. Enhancing the rehabilitation objective design from BSO to IO results in approximately a 23 percent increase in construction cost.

Table 4. Estimated Total Rehabilitation Costs Summary Comparison

| Rehabilitation Objective | Design Fee | Construction Cost | Construction Cost (per SF) | Total Project Cost | Total Project Cost (per SF) |
|---|---|---|---|---|---|
| FEMA 178, Prevailing Practice | $38,000 | $ 76,000 | $ 3.50 | $114,000 | $ 5.20 |
| FEMA 273, Basic Safety Objective (BSO) | 53,000 | 254,000 | 11.50 | 307,000 | 14.00 |
| FEMA 273, Immediate Occupancy (IO) | 60,000 | 313,000 | 14.20 | 373,000 | 17.00 |

Note: SF cost based on a building area of 22,000 SF

The cost for rehabilitation design under prevailing practice methods, including preparation of plans, specifications, and cost estimates, is approximately $37,000. Excluding the costs for the initial learning curve, the design cost using *FEMA 273 Guidelines* is approximately $53,000. The design cost using the *Guidelines* is approximately 40 percent more than that for prevailing practice. Design by FEMA 273 involves distributing, and possibly designing, for two design forces (i.e., BSE-1 and BSE-2), whereas prevailing practice involves a single design base shear. Design by FEMA 273 for this evaluation also requires a greater amount of rehabilitation than that required by prevailing practice.

## CONCLUSIONS

The FEMA 273/274 document provides uniform criteria by which existing buildings may be rehabilitated to attain a range of different performance levels when subjected to earthquakes of varying severity. This unique approach is unlike that adopted presently by building codes for new construction where building performance is implicit and not obvious to the user. Although rational in approach, the *Guidelines* produce a design that costs significantly more than that which results from prevailing practice, since analyses must often be carried throughout design using two force levels due to force and deformation controlled components.

The force level for the FEMA 273 BSO design for this model is approximately 11 times greater than the forces used for prevailing practice design; however, the capacity for primary components in the BSO design is approximately 6 times greater than prevailing practice values. The existing shear wall demand-capacity ratios for the BSO design are, on average, approximately 70 percent greater than the ratios for prevailing practice. The number and size of all members and components designed using the *Guidelines* are greater than the design by prevailing practice. In addition, stricter provisions in the *Guidelines* require additional rehabilitation than that required by prevailing practice. Therefore, both the design and construction costs using the *Guidelines* are estimated to be significantly greater than those using prevailing practice.

Additional work needs to be performed to reduce ambiguities in the *Guidelines*. For example, the default soil classification (Class E) should be evaluated for consistency with the 1997 Edition of the Uniform Building Code (Class D). The requirements for column base plate design should be clarified with respect to increased concrete compressive strength when calculating required bearing area. The method for overturning analysis at the Immediate Occupancy performance level should be presented, and additional research should be performed to qualify the recommended strength and rigidity values on straight and diagonally sheathed shear walls and diaphragms. Overall, many specific requirements in the *FEMA 273 Guidelines* are buried within the text of the document in a descriptive, narrative manner. Presenting the information in a more direct manner, similar to that of a building code, would make it clearer and easier to find and follow. Much of the background discussion and dialogue in the *FEMA 273 Guidelines* should be moved to the *Commentary* for clarity.

## REFERENCES

1. NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency, FEMA-274, October 1997.

2. NEHRP Guidelines for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency, FEMA-273, October 1997.

3. NEHRP Handbook for the Seismic Evaluation of Existing Buildings, Federal Emergency Management Agency, FEMA-178, June 1992.

4. Uniform Building Code™, International Conference of Building Officials, 1997, Vol. 2.

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