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The architectural engineering program at the University of Wyoming offers several courses in the areas of HVAC, Plumbing, Fire Protection, Energy and Building Electricity.

Plumbing is a discipline founded in hydraulics and legal issues governed by codes and standards. This discipline includes, but is not limited to, the design of hot and cold water, storm, drainage and venting systems. Many documents, books and references are available covering the topics associated with plumbing. However, the majority of them are oriented toward plumbing techniques and practical issues.

Within this paper we discuss the integration of plumbing into the Architectural Engineering curriculum, as well as how high-rise plumbing can be taught for engineers. We also discuss how to combine the fundamentals, such as hydraulics, and different codes and standards, to create a successful class. A comprehensive capstone project that will integrate various components of plumbing will be discussed in this paper. The particularity of high-rise plumbing vs. low-rise plumbing is also discussed.

Also, this paper describes the experiences we encountered over the past several years while developing and teaching the plumbing curricula in the Architectural Engineering program. In addition, we describe the history of the architectural engineering curriculum at the University of Wyoming, the plumbing design project, and the building design process.

Most importantly, project methodology will be discussed, including the design of various systems, system selection and commissioning, and will culminate with administrative topics. We demonstrate this methodology through the use of a comprehensive design project.

We discuss this design course from the students' point of view, focusing on the experience gained in design, codes and safety, as well as in written and oral communication skills. We also describe the methods we use in terms of learning outcomes to evaluate the effectiveness of the capstone design program.

Introduction:

Plumbing is a growing area. One decade ago, the plumbing projects focus on hot/cold water, drainage/venting and storm systems. These days, many new subjects have been introduced, such as rainwater harvesting, water reclamation, graywater, green plumbing and so on.

High-rise building, also called high-rise, multistory building tall enough to require the use of a system of mechanical vertical transportation such as elevators. The skyscraper is a very tall high-rise building.

The International Building Code (2009), section 403 defines a high-rise building as a building with an occupied floor located more than 75 feet (22 860 mm) above the lowest level of fire department vehicle access (the level where the firefighting apparatus would stage firefighting operations). The same definition is given by NFPA “Fire Protection Association”. Basically, the number of story is irrelevant and the only consideration is the height of the building. The first high-rise buildings were constructed in the United States in the 1880s. They arose in downtown areas where increased land prices and great population densities created a demand for buildings that rose vertically rather than spread horizontally, thus occupying less precious land area. High-rise are usually residential, multi-purpose commercial buildings or mixed-use buildings.

High-rise buildings are challenging to build architecturally and also they are challenging in term of engineering design, such as pumping cold and hot water, and mechanical uses, such as cooling towers and supplying HVAC equipment (*Larson, 2007*).

Vertical piping systems are generally more economic and need less maintenance than horizontal piping systems in multilevel projects. Vertical piping uses fewer supports, hangers, and inserts and requires less horizontal space in ceiling plenums for sloping to achieve drainage (*Connelly, 2007*). However, the drawback of vertical piping is the multiple penetrations through structural slabs. Each of these penetrations must be sealed or protected to fulfill the requirements of building codes, in term of protecting the building pressurization and also to prevent vertical migration of fire and smoke. The location of these multiple penetrations is critical to the integrity of the structure and the function of the fixtures even more than the aesthetics of the built environment. Tall buildings require more robust structures, further limiting the allowable space for penetrations. Other structural practices, such as post-tensioned beams and slabs, which serve to lighten the overall building structure, can limit even further the available locations for slab penetrations (*Larson, 2007*).

Domestic Water systems:

High-rise plumbing usually uses vertical piping systems in terms of water distribution, drainage/venting. High-rise plumbing has several specificities in comparison to other type of buildings:

Pressure distribution:

Model plumbing codes (as well as *ASPE Data Book*) limit the pressure supplied to a fixture to ($P_{\max} = 80$ psi ~ 550 kPa), where Steele (*Steele, 1984*) mentioned in his book that the maximum pressure should not exceed ($P_{\max} = 70$ psi). There is a 0.433-psi (2.98-kPa) static pressure change for each foot of elevation change. This pressure is relatively small comparatively to sprinkler/standpipes fire protection ($P_{\max} = 175$ psi) (*NFPA 14, 2010*), since the maximum pressure required at fixtures is usually not higher than 25 psi (for most demanding fixture: water closets, supplied with flush valve fixtures).

The pressure required to be generated by the domestic water booster pumps at the base of the plumbing system can be calculated by the following equation:

Residual pressure at the highest fixture + Static pressure + Friction losses = Required pressure -
Minimum available pressure = Required pressure by booster pumps

The second reason to have limitation of water pressure is to limit the water velocity below critical values (~10 fps) for noise considerations and to avoid erosion of piping, water hammer, damage to fixtures and equipment, excessive equipment costs. The objective of a designer is to have a system where the pressure is controlled, usually by either placing pressure reducing valves on each level where pressure exceeds the code maximum or branching from the higher pressure riser to make a pressure zone. This pressure zone uses a central pressure-reducing valve and sub-riser to meet the minimum pressure required at the highest level and the maximum pressure allowed at the lowest level. This particular method has been used successfully in many high-rise building designs (Connelly, 2007).

Other considerations for water distribution system is the building height, available municipal water pressure, pressure requirements at different floor throughout the building and at the upper floor, flow demand, booster pump capacity and control, pipe and valve materials, riser locations, pressure zones, pressure-regulating stations, water heater storage capacity and recovery, water heater locations, domestic hot water circulation or pipe temperature maintenance, space requirements in the building, economics, energy efficiency, and acoustics.

Zoning:

To avoid excessive pressure, several schemes have been developed over years to achieve an economical, efficient and conserving installation. Usually building over 100 feet in height require multiple water distribution zones.

Cold water Distribution:

High-rise buildings use several pumping schemes.

- a. Single zone: Tank at the top will fill pump at the bottom:

The most common system used in the late 1800s and early 1900s consisted of a roof tank(s) combined with constant-speed pumps that operated by a level switch in the tank. When the level in the tank would approach a pre-determined height, the pumps would either turn on to fill the tank(s) or turn off when the tank is full (Larson, 2007). Water storage was also required for fire protection, and tanks provided for both needs. The water is distributed using gravity downfeed arrangement.

- b. Multiple zones: High zone tank and low zone tank: If multiple zones were required, multiple tanks were used. An air gap creates a pressure break between the upper and lower zones. The tanks must be sufficiently elevated for adequate pressure at the first floor connected.
- c. Multi-zone cold water Distribution with Multiple Pumps: Once the reliability of pumps and power supply was established, multiple booster pumps with constant-speed, constant-pressure controls were utilized, with one pump for each zone.
- d. Pressure regulating valves: Pressure regulating valves provided another means of separating the building into zones. With a pumped system, the supply pressure to the lower zone is controlled by PRV, and the pump discharge pressure is set for the supply to the upper zone. An alternative

would be to use a tank as the source, and continue to control the lower zone pressure with a PRV.

Multiple new systems, using pressure regulating valves, inserted off of a common high pressure express main or also be installed at each floor where the pressure exceeds code maximum.

e. Variable-Speed Pumps Systems:

Variable- speed control pumps can be used, which can reduce the energy consumption over the life of the system while increasing system life by years. Because a constant water pressure is desired in the building, various control schemes can be employed to maintain the desired pressure with varying flows.

Variable-speed booster pump systems are fast becoming the first choice for plumbing engineers due to the advantage of reduced equipment and energy costs, the elimination of water hammer and surges found with most constant speed systems and variable speed's ability to maintain accurate pressure settings.

Hot Water Distribution:

- When domestic water distribution is separated into zones, providing domestic hot water becomes more complicated.
- Centralized distribution that is common in single zone systems can be problematic.
 - Simplest approach is to provide water heating specific to each zone, or locally on each floor.
 - Alternatively, a centralized recirculation system can be use, requiring PRV's on the return.

Other multizone hot water recirculation systems exist, such as those with multiple dedicated heaters, or with a single or multiple pumps.

Drainage/venting:

- Terminal velocity:
The drainage is a gravity system, where the water drainage flow (1/3) tends to attach to the piping wall forming a hollow cylinder of water, with a core of air (2/3) in the center, and opposed by the friction forces applied by the pipe asperity. These opposite forces limit the water drainage velocity to the value given by the following equation:

$$V_t = 3.0 \left(\frac{q}{d} \right)^{2/5} \quad (1)$$

The terminal length is given by the equation (2).

$$L_t = 0.052 V_t^2$$

From these equations (1) and (2), the two values are limited as follow:

$$10 \leq V_t \leq 15 \text{ fps and } 10 \leq L_t \leq 15 \text{ feet.}$$

(2)

- Stack Offsets:

A hydraulic jump may occur, in case the fixture layouts change and stacks must be offset (the offset at an angle higher than 45 degrees) to new locations. (a large slug of water can quickly develop) may occur. The impact of these fluid and air fluctuations can be controlled by effective use of yoke vents, relief vents, and vent connections at the bases of stacks. In the same time avoid connection of drainage piping to any zone where hydraulic jump may develop. *Successful methods include increasing the horizontal drain size and/or slope, using thrust blocks, or using restraining joints with threaded rod or similar arrangements that mechanically anchor the fitting to the entering and leaving piping.*

- Expansion and Contraction:

Variation of temperature causes expansion or contraction of stacks soluble gaskets installed in the caulked joints to avoid this problem.

Figure 1. Compression gasket used for building drains or sewers

- Suds Pressure:

In residential buildings, where washing machines, dishwashers, laundry trays and kitchen sinks create an additional pressure due to the significant amount of suds. The mixture water, suds and air flow down and accumulate at the lower sections of the drainage system and at any offsets greater than 45 degrees in the stack. The drainage and vent piping for the lower floor fixtures or for the fixtures above offsets must be arranged to avoid connection to any zone where suds pressure exists.

Venting:

The venting system objective is to take the excess of air outside the drainage system and neutralize the pressure within the system.

Case Study:

In this part, we present a case study developed by the students. The objective of this project is to convert an existing plumbing of a commercial building in China to fulfill the international plumbing code (2009), as well as international building code (2009). The actual code is the Chinese code. The methodology followed is as follow:

- 1) Determination of the number of building occupants and the minimum number of plumbing fixtures floor by floor
- 2) Sizing the drain, waste and vent systems
- 3) Domestic water system load
- 4) Domestic water system size.
- 5) Special design of this building
- 6) Comparison between the Chinese design and the design according to the international codes.

This process is represented in the Figure 1. The building is a high-rise, 15 story office building, with 4 stacks. The floor plan of the basement floor is represented in Figure 2.

Basement:

1st floor:

2nd floor:

3rd floor:

Figure 2. Floor plans for the high-rise building studied

Basement consists of garage area (9139.8 ft²) and miscellaneous spaces (5080.6 ft²). The first floor is a showing room (4696.8 ft²) and miscellaneous spaces (972 ft² and 1540 ft²). The rest of floors are office spaces. Using the international building code has been used to determine the number of occupants and later the number of fixtures. This number has been compared to the actual number of fixtures determined from Chinese plumbing code (Table 1).

The drainage system of the high-rise building (Figure 4) has been sized according to the international plumbing code (IPC, 2009). A comparison between the actual sizing using the Chinese code has been performed (Table 2).

Figure 3. Flow chart used to compare the actual design (China) to IPC (2009)

Table 1. Actual number of fixture (China) and the fixture number from IPC (2009)

Basement			4th~7th floors			3rd floor		
For male			For male			For male		
	Required	Actual		Required	Actual		Required	Actual
WC	1 or 2	0	WC	1 or 2	3	WC	2 or 3	2
Lava.	1	0	Lava.	1	2	Lava.	1 or 2	2
Urinal	1	0	Urinal	1	3	Urinal	1 or 2	2
For female			For female			For female		
WC	1 or 2	0	WC	1 or 2	2	WC	2 or 3	2
Lava.	1	0	Lava.	1	2	Lava.	1 or 2	2
1st floor			8th~13th floors			Top floor		
For male			For male and female			For male		
	Required	Actual		Required	Actual		Required	Actual
WC	1 or 2	2	WC	3	8	WC	0 or 1	0
Lava.	1	2	Lava.	1	8	Lava.	0 or 1	0
Urinal	1	2	14th floor			Urinal	0 or 1	0
For female			For male			For female		
WC	1 or 2	2		Required	Actual	WC	0 or 1	0
Lava.	1	2	WC	1 or 2	3	Lava.	0 or 1	0
2nd floor			Lava.	1	2			
For male			Urinal	1	3			
	Required	Actual	For female					
WC	1 or 2	2	WC	1 or 2	2			
Lava.	1	2	Lava.	1	2			
Urinal	1	2						
For female								
WC	1 or 2	2						
Lava.	1	2

Figure 4a: Drainage System

Figure 4b: Drainage System

Figure 4c: Drainage System

Figure 4d: Drainage System
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Table 2. Results of the comparison between the actual building (China) and the IPC (2009):

Section of pipe	Definition	DFU	Mini. Size (inch)	Actual size(inch)	Table used	Modified size (inch)
Section 1 of PL 1	Stack	72	4	4	Table 6-2	6
Section 2 of PL 1	Building drain	72	4	4	Table 6-1	6
Section 1 of PL 2	Stack	36	2 ^{1/2}	4	Table 6-2	6
Section 2 of PL 2	Building drain	36	4	6	Table 6-1	
Section 1 of PL 3	Stack	36	2 ^{1/2}	4	Table 6-2	6
Section 2 of PL 3	Building drain	36	4	6	Table 6-1	
Section 1 of PL 4	Stack	53	4	4	Table 6-2	6
Section 2 of PL 4	Building drain	53	4	4	Table 6-1	6
Section 3 of PL 4	Stack	98	4	4	Table 6-2	6
Section 1 of PL 5	Stack	36	2 ^{1/2}	4	Table 6-2	
Section 2 of PL 5	Building drain	36	4	4	Table 6-1	6
Section 3 of PL 5	Stack	36	4	4	Table 6-2	6
Section 4 of PL 5	Building drain	36	4	4	Table 6-1	6
Section 1 of PL 6	Stack	36	2 ^{1/2}	4	Table 6-2	6
Section 2 of PL 6	Building drain	36	4	6	Table 6-1	
Section 1 of PL 7	Stack	36	2 ^{1/2}	4	Table 6-2	6
Section 2 of PL 7	Building drain	36	4	6	Table 6-1	
Section 1 of PL 8	Stack	70	4	4	Table 6-2	6
Section 2 of PL 8	Building drain	70	4	4	Table 6-1	6
Section 3 of PL 8	Stack	142	4	4	Table 6-2	6
Section 1 of PL 9	Stack	60	4	4	Table 6-2	6
Section 2 of PL 9	Building drain	60	4	4	Table 6-1	6
Section 3 of PL 9	Stack	60	4	4	Table 6-2	6
Section 4 of PL 9	Building drain	60	4	4	Table 6-1	6
Section 1 of PL 10	Building drain	144	4	6	Table 6-1	
Section 2 of PL 10	Stack	144	4	6	Table 6-2	
Section 3 of PL 10	Building drain	144	4	6	Table 6-1	
Section 1 of PL 11	Building drain	240	5	6	Table 6-1	8
Section 2 of PL 11	Stack	240	5	6	Table 6-2	8
Section 3 of PL 11	Building drain	240	5	6	Table 6-1	8
Section 1 of PL 13	Stack	16	2	2 ^{1/2}	Table 6-2	3
Section 2 of PL 13	Building drain	16	3	2 ^{1/2}	Table 6-1	4

Evaluating Student Performance

Student performance in this specific course is evaluated, and their progress is monitored, by the instructor, who will assign a grade for the course. Although varied to a limited extent, the assignment of the grade is generally based on (a) homework problems, (b) quizzes and mid-term exams, (c) final exam, (d) project, and (e) other assignments including presentation of projects, which is required in this course.

This course requires a group project involving a complete design that may contain a host of modules including architectural plumbing drawings, hot/cold water design, drainage/venting system, cost estimating and bid document preparation, etc. This course is a multi-disciplinary effort; and as such our objective is to make involve students from other disciplines in addition to those in architectural engineering. The student performance in this course is evaluated through weekly progress reports by students, mid-term presentation of project progress, final presentation of the project (power point presentation and poster presentation), examination on the learning objectives, results of ethics study (including preparation of a code of ethics by students), and preparation of a complete project report that contains all design drawings and calculations. This course also involve leadership and oral and writing components as part of their learning objectives.

The student performance in courses involving laboratory also includes evaluation of laboratory reports required from students. Grading of laboratory reports is rigorous and involves evaluation of technical contents, clarity and coherence of presented materials, and writing skills.

Most of the architectural engineering senior level courses also involve projects. In addition to homework problems, exams, etc. the student evaluation in these courses is also achieved through review of their final project reports and in some cases the oral presentation of their work.

Future plans to evaluate the effectiveness of the curriculum in term of learning outcomes:

Actions that will be implemented to improve the effectiveness of the curriculum in term of learning outcomes:

- We expanded on the instructors' self-evaluation such that more direct assessment of students' learning outcomes is obtained. A set of standards for instructor's self-evaluation will be prepared by the faculty and the Board of Advisors and will be implemented with the annual assessment cycle. The main point of these standards is that the evaluation of students' performance will be based on samples of work in three categories of students: those in the upper 75 percentile, those in the 50 – 75 percentile and those below the 50 percentile populations. Thus the assessment results compiled are based on course performances and grades, exams, projects, presentations of students, and writings as required in some courses. Furthermore, each course specifically addresses the learning outcomes and relation between the course and the Program outcomes, the methods used for the evaluation of students' performance and the relevance of the course materials to the Program outcomes following the standards adopted for the assessment process.
- Students will be provided with the course descriptions including learning objectives and outcomes. Students also will provide their input on the Program outcomes. The results from this

instrument are used along with those from the instructors' self-assessment of courses as a means to ensuring compatibility in results obtained.

- A more rigorous process in assessing the learning outcomes of the capstone courses will be implemented, which are in parallel with the Program outcomes. The following outlines process will be used for the capstone course assessment.
 - Individual instructor evaluation of the degree of learning achievement of individual students on a capstone team, which includes consideration of the collective achievements of the team.
 - Peer evaluation (optional by instructor).
 - Grading of deliverables by the instructors (project plan, mid-term review, final report, exhibit (and abstract), oral presentation, team minutes, web site if applicable).
 - Teamwork survey.
 - Self-assessment.
 - Senior Design Symposium judging (with evaluation criteria explicitly indexed to the learning objectives and articulated via rubrics for all measures).

Conclusions:

High-rise buildings are challenging to build architecturally and also they are challenging in term of engineering design, such as pumping cold and hot water, and mechanical uses, such as cooling towers and supplying HVAC equipment. In this paper, we exposed the summary of the methodology followed to teach high-rise plumbing.

A case study has been developed to demonstrate the difference between plumbing designs in other countries, such as China where the venting system is not required. We presented the results of comparison between the two codes.

This design class has been positively accepted by the students, and has provided them with a comprehensive experience in both design and systems integration. Students are required to use multiple codes and make the comparison between several designs and codes. Finally, it provides the students an opportunity to improve their skills in both written and oral communication.

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