Lecture material summary

Purpose of this document:
Teaching material for lecturers in Architecture and Civil Engineering. Can be used as a whole or as separate sections.
Prepared by an ISSF* Task Force

Members:

- Eduardo Carragueiro (Böllinghaus)
- Thiery Cremailh (Schmolz + Bickenbach)
- Bernard Heritier (ISSF)
- Clara Herrera (Deutsche Edelstahl Werke)
- Jun Ishikawa (ISSF)
- Marco Massazza (Cogne Acciai Speciali)
- Thomas Pauly (Euro-Inox)
- Luis Peiro (Acerinox)

* International Stainless Steel Forum, Avenue de Tervueren 270, B-1150 Brussels www.worldstainless.org
Reviewed by an Advisory Committee

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Test your knowledge of stainless steel

A quiz in which you can test your knowledge of stainless steel is now available:
https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 01

Art
Andy Scott: The Kelpies

Andy Scott: "The original concept of mythical water horses was a valid starting point for the artistic development of the structures. I took that concept and moved with it towards a more equine and contemporary response, shifting from any mythological references towards a socio-historical monument intended to celebrate the horse’s role in industry and agriculture as well as the obvious association with the canals as tow horses."

Location:
Falkirk, Scotland

Material:
Structural Steel
Cladded with type 316L (S31603) Stainless Steel

Dimensions:
30 metres high

Weight:
300 tonnes each

Year created:
2013
The Atomium was constructed for the 1958 Brussels World Fair. Its nine spheres are connected so that the whole forms the shape of a unit cell of an iron crystal magnified 165 billion times. It was renovated between 2004 and 2006. The renovations included replacing the faded aluminium sheets on the spheres with stainless steel. CNN named it Europe's most bizarre building! It is one of the major attractions of Brussels.

**Location:**
Brussels, Belgium

**Material:**
Polished 1.4404 (316L) stainless steel

**Dimensions:**
102 meters high with each of the nine spheres having a diameter of 18m

**Weight:**
2400 tons

**Year created:**
1958


The Atomium was constructed for the 1958 Brussels World Fair. Its nine spheres are connected so that the whole forms the shape of a unit cell of an iron crystal magnified 165 billion times. It was renovated between 2004 and 2006. The renovations included replacing the faded aluminium sheets on the spheres with stainless steel. CNN named it Europe's most bizarre building! It is one of the major attractions of Brussels.
Intended to be “A suitable and permanent public memorial to the men who made possible the western territorial expansion of the United States...”, the gateway Arch in St Louis, MO, USA, is 192m tall, the world’s tallest arch, and has become the symbol of St Louis. The arch weighs 4164T, of which 803T of AISI 304 stainless steel cladding.
Sir Anish Kapoor: Cloud Gate

Cloud Gate is British artist Anish Kapoor’s first public outdoor work installed in the United States. The 110-ton elliptical sculpture is forged of a seamless series of highly polished stainless steel plates, which reflect Chicago’s famous skyline and the clouds above. A 12-foot-high arch provides a “gate” to the concave chamber beneath the sculpture, inviting visitors to touch its mirror-like surface and see their image reflected back from a variety of perspectives. Inspired by liquid mercury, the sculpture is among the largest of its kind in the world.

**Location:**
Chicago, USA

**Material:**
Highly polished 304 stainless steel plates

**Dimensions:**
10 by 20 by 13 m

**Weight:**
110 tonnes

**Year created:**
2004
Anilore Banon: Les Braves ⁹ - ¹¹

This memorial stands on the beach known as Omaha Beach in the village St. Laurent-sur-Mer in Normandy, France and commemorates the soldiers that fell on the beaches of Normandy on D-Day, June 6, 1944. The memorial was dedicated on June 5 2004, for the 60th anniversary of the landing.
The principal concept in this piece is that of dialogue. The two figures face one another as if in perpetual, silent conversation. The title, *Mirror*, is the act that the figures perform for one another — standing as reflections of the other’s thoughts and dreams. There is room enough between the two figures for the viewer to stand and “enter” the conversation. The figures are modeled in letters from eight alphabets – Arabic, Chinese, Greek, Hindi, Hebrew, Japanese, Latin and Russian. The artist considers this dialogue and interaction as central to learning, and more importantly to understanding, between people and cultures.
Louise Bourgeois: Maman

The title *Maman* enhances dynamic contradictions at the heart of the sculpture. Why the spider? "Because my best friend was my mother and she was deliberate, clever, patient, soothing, reasonable, dainty, subtle, indispensable, neat, and as useful as a spider. She could also defend herself, and me, by refusing to answer 'stupid', inquisitive, embarrassing, personal questions”
Eila Hiltunen: Sibelius Monument (1967)

The Sibelius Monument in Helsinki, Finland, is dedicated to the Finnish composer Jean Sibelius. Weighing around 24 tonnes, the sculpture is made up of more than 600 stainless steel tubes, welded together in a wave-like formation which resembles the shape of organ pipes.
Monica Bonvicini: Hun Ligger (She Lies)  

It is a permanent installation, floating on the water in the fjord on a concrete platform next to the Oslo Opera House, 12m above the water surface. The sculpture turns on its axis in line with the tide and wind, offering changing experiences through reflections from the water and its transparent surfaces.
Sir Anish Kapoor: Turning the world upside down

The stainless steel piece is 5 m tall and 5 m in diameter and flips the whole city of Jerusalem into the sky, signifying the spiritual importance of Jerusalem as a heavenly city.
Jon Gunnar Arnason: Sun Voyager

“Sun Voyager is a dreamboat, an ode to the sun. Intrinsically, it contains within itself the promise of undiscovered territory, a dream of hope, progress and freedom”. The sculpture is located by Sæbraut, by the sea in the centre of Reykjavík, Iceland.
Robin Wight: Fantasywire

UK sculptor Robin Wight creates dramatic scenes of wind-blown fairies clutching dandelions, clinging to trees, and seemingly suspended in midair, all with densely wrapped forms of stainless steel wire. The artist currently has several pieces on view at the Trentham Gardens. 
http://www.fantasywire.co.uk/
Architect Jaime Latapi Lopez: Cristo de Chiapas  

Cristo de Chiapas is an impressive cross, which is coated with gold-colored stainless steel accentuating the figure of Christ and shines in the reflection of the lights of the sun.

**Location:**
Tuxtla Gutierrez, Mexico

**Material:**
Coated Stainless Steel

**Dimensions:**
48m (62m with the base)

**Weight:**
2000 tonnes

**Year created:**
2007
Joana Vasconcelos: Marylin (2009)  

*Marilyn* takes the form of an elegant pair of high-heeled sandals, whose enlarged scale results from the use of saucepans and their respective lids. The unlikely yet assertive association between the saucepans and high-heeled sandals, two paradigmatic symbols of Woman's private and public dimensions, proposes a revision of the Feminine in the light of the practices of the contemporary world. The recourse to saucepans, sign to which one would associate the traditional domestic sphere of Woman, in order to reproduce an enormous high-heeled sandal, symbol of beauty and elegance demanded by social conventions, contradicts the impossibility of the dichotomic relation of the Feminine in the domestic and social spheres. The represented object thus emerges as panegyrical of the feminine duality, insinuating the full realization of individuality through the subversion of the social norm.

**Location:**  
Versailles, France

**Material:**  
Stainless Steel

**Dimensions:**  
3m x 1.5m x 4m

**Weight:**  

**Year created:**  
2009
Jeff Koons: Sacred Heart Red/Gold ... \(^{22}\)

“...acidly comments on the commercial debasement of emotional and religious experience.”

(NY Times)
Gil Bruvel: Dichotomy

Inspired by the complexities of living fully in all worlds at once, Dichotomy meditates on and celebrates the dual nature of existence. Composed of “ribbons of energy” that seek to capture the process of engaging all levels of being in order to be fully human, the sculpture reflects the natural strength and quiet majesty inherent in integrating the various levels of existence. As a result, the figure inhabits a serene meditative space, fully embracing a dichotomy of existences: anima and animus, male and female, conscious mind and unconscious mind, waking and dreaming.
David Černý: Metamorphosis

The structure is comprised of seven separate layers that rotate intermittently, dissecting the sculptures features. Custom-written programs control motors embedded within the structure to orchestrate choreographed sequences. Every motor has a feedback switch so the computer knows where each piece is at any given moment, allowing for random motion within the sequences. This movement is controlled via the Internet by David himself and represents a continuation of his work that incorporates mechanical engineering and computers as an integral part of the design. Live streaming video of the sculpture in motion can be viewed online at www.metalmorphosis.tv
Linda Bakke: The Big Elk

The Big Elk, which was designed by Norwegian artist Linda Bakke, stands on the Bjøråa picnic area in Stor-Elvdal municipality midway between Oslo and Trondheim in Norway. This landmark, apart from its being inherently beautiful, is to attract drivers attention and increase road safety as it invites drivers to stop and stretch their legs and rest, thereby combatting fatigue. The Big Elk has also focused attention on the animals and has become a regional symbol.

Sparebanken Hedmark art fund provided NOK 2 million (207,000 euros) to produce the sculpture.

http://lindabakke.webs.com/sculptureskulptur.htm
Chen Zhen: La danse de la fontaine émergente ²⁶

The fountain, designed by the French Chinese artist is designed to resemble a dragon winding its way around the square, emerging and submerging from the pavement. The dragon's transparent skin shows the water flowing within.

The fountain is in three parts. An opaque bas-relief dragon appears to emerge from the water-supply plant wall and plunge underground. The transparent second and third parts show the dragon seeming to arch out of the pavement. Water under pressure flows within and is illuminated at night. The fountain was commissioned by the City of Paris in 1999 and inaugurated on February 6, 2008. Although the artist died in 2000, he left sketches showing how the fountain should look like and was completed by Xu Min, the sculptor's spouse and collaborator. The fountain did cost 1,2M€, largely financed by the City of Paris and the Ministry of Culture of France.

El Peix d’Or is a mesh sculpture in the form of an open-mouthed undulating fish. It is made of stone and steel. Its copper-colored stainless steel scales shine under the Mediterranean sun and change appearance depending on the angle of the sun and the current weather conditions, accentuating the organic form of this vast sculpture.

The Golden Fish called El Peix d’Or in Catalan, was designed for Barcelona’s 1992 Olympic village and port. The golden coloured steel structure serves as a canopy for the commercial area which links the luxurious Hotel Arts to the seafront near the Olympic Marina. It is one of the best-loved and most striking iconic landmarks on Barcelona’s seafront.

Zhan Wang + Atelier Deshaus: Blossom Pavilion

The starting point for the project was the stainless steel sculptures of Zhan Wang’s Rockery Series, which the artist has been working on since 1995. Atelier Deshaus reinterpreted these forms as structural elements, aiming to create a pavilion modelled on a rock garden. Six slender rock-shaped columns support a solid steel roof, which is topped by plants and flowers. The reflective columns are arranged randomly, rather than at the most structurally efficient points, to reinforce the idea of a rockery.

https://www.archdaily.com/792211/blossom-pavilion-atelier-deshaus/5799b693e58ece81bd00004a-blossom-pavilion-atelier-deshaus-photo
Martin Debenham: mermaid 3

British contemporary sculptor Martin Debenham creates stainless steel wire sculptures inspired by fantasy and nature. Working with a malleable material that has endless potential, the self-taught artist’s growing collection of wire art features impressive structures rendered from intricate twists, bends, and expert welding. Appearing as though they’re three-dimensional line drawings, most of Debenham’s metal masterpieces are made for outdoor display. When placed into natural environments, they seem to evoke mythical narratives as they glimmer in the sunlight. For example, in one piece, a wire-sculpted mermaid sits on a rock by a lily pond, positioned as though she’s contemplating going for a swim. Each strand of wire is sculpted into curves that follow the form of the female body, then flow into a long mermaid tail.

https://mymodernmet.com/wire-sculptures-martin-debenham/
Robert Gahr: Surge

Wall Sculpture

Location:

Material:
polished & colored stainless steel

Dimensions:
3 panels of 1mx1m each

Weight:

Year created:
2011
Ralfonso Karo: #1 Kinetic Wind Sculpture

25 diamond shaped stainless steel elements connect, self-balance and move independently in the wind. Click here for video (4’:51’’).
Sun Hyuk Kim: Forgotten Memory

Artist Sun-Hyuk Kim takes inspiration from complex root systems found in nature to construct the human form. Each sculptural figure sprouts a branch or sometimes a small tree, appearing to be some type of human-botanic hybrid. The large, stainless steel sculptures feature fragments of faces, headless bodies, and figures crouching towards the ground as if they are overcome by a great weight on their backs.

Kim’s minimalist sculptures allow us to project ourselves onto each of his pieces. They communicate fragility. We all know how it feels to be pulled in different directions and the often-uncomfortable state of growth and change. But in having this knowledge, it connects us together and reminds us that the human experience is vast and ever-changing—just like that of a tree.
And there is a lot more!

http://www.worldstainless.org/applications/art

If you have other remarkable works of art in mind, please let us know!
References (1/3)

11. https://www.youtube.com/watch?v=yHkOQWPZhyM
References Art (2/3)

33. https://www.sunhyuk.com/sculpture
Thank you!

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Module 02A: Applications - Architecture
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11. Swimming pools
1. Facades
Clockwise, from top left:

1. Westfield Doncaster shopping center facade in Victoria, Australia

2. Sunbreaker Stainless mesh ion a school facade near Whashington, DC, USA. Reduces glare, saves energy offers good visibility

3. Stainless mesh canopy over courtyard, Arizona, USA. Maximizes sun blockage while allowing air flow

4. Lou Ruvo medical Research Center designed by Frank Gehry, Las Vegas, USA
Stainless facade of 285m-high apartment building, New York, USA.

Architect: Frank Gehry
Reflective stainless steel inserts in a concrete wall for an archive building, Bure-Saudron (51), France
F. R. Weismann Art Museum, Minneapolis, USA (1993)
Architect: Frank Gehry

Gehry: "I always have felt that architecture was about materials. Watching my artist friends work directly with materials – the right product is something that seems right and real and acceptable and not contrived."

For the Weisman, Gehry chose stainless steel... Its shiny, reflective, but extremely durable surface has given the building its unique identity.
Kauffman Center of Performing Arts, Kansas City, ISA (2011)
Architect: Moshe Safdie; Engineering: Arup

The north elevation of the building, which faces downtown Kansas City, features a series of arched walls sheathed in stainless steel that rise from the ground like a wave. From its crest a curved glass roof sweeps down towards the low-rise Crossroads neighborhood to the south and cascades into a 65-foot high by 330-foot wide glass wall, which provides the Kauffman Center's Brandmeyer Great Hall with panoramic views of Kansas City. This dramatic glass facade and roof are anchored by 27 high-tension steel cables, reminiscent of a stringed instrument.
Len Lye Centre, New Plymouth, NZ
Architect: A. Patterson

14 m high facade made of 32 tons of highly polished grade 316 stainless steel
Delhi Metro Rail Corporation Headquarters, India
Architect: Raj Rewal & Associates$^{12}$

Architect Raj Rewal & Associates designed stainless steel cladding for the building in New Delhi, involving stainless steel tubular truss with stainless steel panels interspersed with toughened glass panels.
District heating facility, Torino, Italy

Architect: JP Buffi

The heating facility has been clothed by curved screens. The copper-coloured stainless strips are arranged to provide gaps for a glimpse through to the facility.
Capital gate Tower (2010), Abu Dhabi
RMJM, Architects

The distinctive stainless steel ‘splash’ that descends from the 19th floor, is a design element and a shading device that eliminates over 30 percent of the sun’s heat before it reaches the Capital Gate building. The splash also twists around the building towards the south to shield the tower as much as possible from direct sunlight.

The ‘splash’ is made of 580 panels for a total of ~5000 m² of stainless steel mesh.
Glass facade

A web of stainless steel tie-bars linked by nodes holds the glass facade, maximizing open light area, including corners
Glass facade, Paris

The glass facade is supported by a light, high strength stainless steel structure. The sphere in the background is the «Geode», a unique stainless steel clad 360° movie theater, part of the «Cité des Sciences et de l’industrie».
Glass facade, Paris$^{19}$
Office building mesh facade, Utrecht, Netherlands
Architects: Cepezed

This 3000 m² stainless steel mesh facade holds transparent plastic disks. Wind causes the mesh to vibrate and the disks to move, resulting in ripples and light effects.
Energy saving building, Nantes, France
Architects: FORMA 6 & B. Dacher

Intricate laser cut shapes of the stainless steel facade give this building an outstanding look.
McGowan Academic center,
Washington, DC, USA
Sunshade mesh⁶

McGowan Academic Center is a classroom building community college.
The building design provided for an atrium area integrated with an exterior ventilated façade, in the center of the building that faced directly east in the morning hours.
The stainless sunshade reduces the daytime glare and the amount of air conditioning required to cool the space in the summer months. Typical metal sunshade products could not be used for this application as visibility was crucial. They simply didn't offer enough open area.
Rehab of Château de Rentilly, France

Left: Before  
Below: After

A contemporary art building in the park of a château. The facade has been clad with mirror-finish stainless steel plates

Xavier Veilhan, architect: «... the building was a shadow of what it was.... I wanted walls that would reflect the surrounding park... »
St Guy Hospital, London

Architect: T. Heatherwick

The Boiler Suit, a unique façade designed to encase the boiler house which powers Guy’s Hospital. It is made up of 108 undulating tiles of woven stainless steel braid and is illuminated at night to provide a distinctive welcoming beacon for staff and visitors arriving at hospital in the dark.
American Airlines Arena, Miami, USA

Made from 3,400 square feet of a high-grade architectural woven stainless steel mesh fabric with interwoven LED profiles, Miami’s Mediamesh® screen, provides visitors to the Arena with unobstructed viewing from the interior and visually engaging digital media content on the exterior. Standing three-stories tall (42 feet high by 80 feet wide), Miami’s Mediamesh façade is four times the size of an average billboard. The arena host more than 1.3 million guests per year for concerts, family and sporting events.
Facades References (1/2):

5. http://wikimapia.org/7695594/Cleveland-Clinic-Lou-Ruvo-Center-for-Brain-Health#/photo/3116187
7. https://newyorkbygeehry.com/
Facades References (2/2):

17. http://hda-paris.com/
2. Green Walls
About Green Walls

Green Facades are an emerging architectural element, providing an enormous amount of benefits to a building through occupant amenity, thermal control and improving air quality.

Using stainless steel cables, rods and mesh to train climbing plants up a building facade provides an alternative to the traditional planted green wall.

Retro-fitting a green facade to existing structures is easily achieved.
Green facade\textsuperscript{1}

Electric transformer building, Barcelona. Stainless fasteners and cables support the plants.
A few years later. Improved aesthetics.
Green walls for apartment buildings \(^2\)
(affordable everywhere!)

Advantages:
• Improved insulation
• Noise damping
• Cooler micro-climate
• Enhanced biodiversity
• Better air quality (pollutants filtration)
• Aesthetics
• Psychological well-being
• Positive social and economic fallout

Stainless cables and anchors
Green walls for apartment buildings\textsuperscript{2}

The benefits of re-introducing Mother Nature to an increasingly unnatural environment are so apparent that the Australian Government has established the Green Building Council of Australia (GBA) to advocate sustainable property development.
Vertical Landscaping

Melbourne City Council Chambers: The stainless steel trellising systems and components provide essential climbing structure for the plant life, and transform the hard heat retaining surfaces into vibrant vertical gardens.
Green wall$^3$
Infrared photography demonstrating temperatures of the building surface, Tampa, AZ. °F, from ref. 4.
Anchors and cables
Stainless steel systems are easy to install
Green Walls References

3. Roofs
## Usual characteristics of stainless steel roofs\textsuperscript{1-4}

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<td>1.4509 1.4510</td>
<td>1.4301 1.4401</td>
</tr>
<tr>
<td><strong>Joining</strong></td>
<td>Mechanical</td>
<td>Welding (for water tightness)</td>
</tr>
<tr>
<td><strong>Surface Finish</strong></td>
<td>Matte or terne coating (Sn)*</td>
<td>Matte or 2B (when there is a top layer)</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>0.5mm; 0.4 mm for rainwater goods</td>
<td>Allows a lightweight structure</td>
</tr>
<tr>
<td><strong>Life expectancy</strong></td>
<td>Will last the life of the building</td>
<td></td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Suitable for green roofs</td>
<td>In renovation can be placed directly on the bitumen roof</td>
</tr>
</tbody>
</table>

* In some areas Cu or Zn are restricted as being eco-toxic and leaching into the rainwater
A new concern, metal runoff in rainwater\textsuperscript{5}

Mostly in northern Europe ... Stems from demands on water quality, availability and re-use
The library, ~ 55,000 m², had its height restricted to avoid obstructing the Parliament House. The central focal dome comprises a lattice of stainless steel tubular members and cables converging at key tension cast nodes. The second dome containing stainless steel tubes, known as the VIP dome, has a diameter of 16 m and a height of 2.5 m.
Clockwise, from top left:

1. Stainless church roof, Leicester, UK
2. School restaurant, Oyonnax, France
3. Universum Science centre, Bremen, Germany
UAE Pavilion at the Shanghaï Expo
Architects: Foster & Partners

The dune-like structure is made of triangulated lattice covered with flat stainless steel panels. It has been designed to be demounted.
New Doha airport, Qatar⁹-¹⁰
Architects: HOK

The undulating roof is said to be the largest stainless steel roof in the world (195000m²).

It features a non-directional, low gloss, uniformly textured stainless steel finish.

A lean duplex grade was selected.

No maintenance is required.
Green Roofs

**Advantages**
- Mitigate heat islands
- Reduce dust
- Promote biodiversity
- Provide insulation
- Reduce flood risks
- Reduce noise
- Absorb CO$_2$

**Aesthetics**
- Psychological well-being
- Positive social and economic fallout

**Limits**
- Requires a sturdy structure
- Needs a proper know-how
- May need watering in summer
- Some maintenance is required
- More expensive
High Reflectance Roof
Austin Hall Sam Houston State University Huntsville, Tx, USA (1851)
Low glare*, high reflectance stainless steel roof

High Reflectance (Albedo) roofs mitigate heat islands in cities.
Solar Reflectance is now included in LEED (Leadership in Energy and Environmental Design)
SRI of Proprietary finishes > 100

* The surface must provide a diffuse light reflection (i.e. avoid mirror-like reflection). Highly polished surfaces are not suitable.
Sunbreakers$^{15}$
University of Arizona Medical Research Building &
Thomas Keating Bioresearch Building

Canopy-type shading
Mesh with 43% open area: maximises sun blockage while allowing air to pass between the panels.
Roofs References

    b) http://www.wbdg.org/resources/cool-metal-roofing
15. www.cambridgearchitectural.com/
4. Decoration
Clockwise, from top left:
1. Wood and stainless stairs (unspecified location)
2. Curved wire mesh ceiling (Louisiana State University)
3. Restaurant in Finland with transparent room divider
4. Door handle
Banque de France, Paris, France

Architects: Moati -Rivière

Mirror finish EN 1.4301 (AISI 304)
Metro station L5 El Carmel, Barcelona, Spain

Woven stainless steel mesh wall panels
**Mosteiro da Batalha, Portugal**

Stainless steel mesh curtain  
Open Area 36 %  
Weight 0.25 kg/m²  
Rod diameter 0.05 mm.  
Wire pitch 0.13 x 0.13 mm.
Home curtain/safety banister

- Stainless steel
- Open area 44%
- Weight 5.2 kg/m²
- Cable diameter 4 x 0.75 mm.
- Rod diameter 1.5 mm.
- Cables pitch 26.4 mm.
- Wire pitch 3 mm.
Museum of contemporary art & planning exhibition, Shenzhen, China (under construction)
Architect: CoopHimmelblau
Decoration References

5. Stainless Steel Plumbing
Clockwise, from top left:
1. Sanitary piping
2. Press-fitted tubes
3. Kitchen faucet
4. Shower head with light
Stainless piping system
Stainless Steel Plumbing References

3. https://nickelinstitute.org/library/?opt_perpage=20&opt_layout=grid&searchTerm=pipes%20for%20buildings&page=1
5. https://www.grohe.de/de_de/badezimmer.html
6. Escalators and elevators
Clockwise, from top left:
1. Elevator (unspecified location)
2. Escalator (Prague Metro)
3. Moving sidewalk (Brussels Metro)
Mesh-clad elevator
Kraaiennest metro station entrance, Amsterdam, NL
References:

7. Airports
Clockwise, from top left: stainless equipment at Montreal Airport, Canada
1. Boarding counter, Balustrade and Garbage bin
2. Drinking fountain
3. Bar counter and footrest
Clockwise, from top left:
1. Baggage delivery belt, Manila Airport, Philippines
2. Moving sidewalk, Montreal Airport, Canada
3. Security net in Copenhagen Airport, Denmark
Airports References

Stainless steels are used everywhere, as the requirements are materials are expected to be used by the public 365 days a year while retaining an excellent aesthetic appearance:

- roofs,
- urban furniture,
- counters,
- drinking fountains,
- partitions,
- ventilation equipment
- handrails
- elevators, escalators, moving sidewalks
- baggage delivery carousels
- pushcarts
- fasteners
- etc...
8. Urban furniture
Clockwise, from top left:

3. Handrail, India
4. Lower Manhattan's South Ferry Subway Terminal “See it split, see it change” by by Doug and Mike Starn
Clockwise, from top left:

1. Bench in Paulinia (SP), Brazil. Grade: 304 STS304 Satin Finish
2. Butterfly bench in San Luis Potosi, Mexico
3. Bench with woven mesh, France
Clockwise, from top left:

2. Bicycle rack, Albenga, Italy. Grade: EN 1.4301 (AISI 304)
4. Joana Vasconcelos’s sculpture entitled « Marylin » and made of stainless pots
Urban Furniture References

9. Restoration
Left: Stainless steel entrance pavilion to the crypt of the St Martin-in-the-Field Church, London

Right: Stainless and Glass Pyramide du Louvre, Paris
Opera theatre in Verona, Italy

The great Roman monument, dates back to the first half of the 1st Century AD and has been known as the most important open air opera theatre. Recent restoration work involved the construction of new covering for the central pit, where the orchestra sits, the underground room and the underground sewage tunnels. The new covering slab is supported by a system of roof struts and post tension tie rods. The post tension system used, comprising stainless steel bars, guarantees structural safety, quality and durability.
Roman Theater, Frejus, France

Restoration of the open air roman theater with teck and perforated 3 mm thick EN 1.4571 stainless steel sheet
Restoration References

10. Arenas
Clockwise, from top left: 1-3
1. Handrail in VIP entrance staircase, Wembley, UK; 2. Turnstile; 3. Lockers; 4. Stainless canopy and handrail on Bourke St pedestrian bridge to Melbourne’s Colonial stadium, Australia
Yamuna Stadium, Delhi, India

Architects: Peddle Thorp

On the occasion of the Commonwealth Games 2010, a multifunctional stadium was created in New Delhi. With its shining façade made of stainless steel mesh, the stadium symbolises sport as a means for modern and sustainable human interaction. The stainless steel cladding with an open area of 53 percent shields spectators from the fierce subtropical climate and provides effective sun protection.
Castelão Stadium, Fortaleza, Brazil\textsuperscript{5,6}

Architect: Vigliecca & Associados

The façade was entirely made of stainless steel expanded sheets. In addition to the external frame, stainless steel was used on railings, handrails at VIP areas, lavatories and locks of the stadium. “We have made an option for the durability stainless steel provides, which is essential to areas like the façade that required a corrosion-resistant material, and for its noble appearance, required in the hospitality sector”, says architect Ronald Fiedler, responsible for the Project.
Allianz Park Palmeiras Stadium, Sao Paulo, Brazil
Architect: Edo Rocha Arquitetura

This is one of the most beautiful arenas in the world. Stainless Steel is intensively used in its façade. Stainless Steel is intensively used in its façade. The sheets of stainless steel have holes in them to facilitate the circulation of air.
Media Facade, Lille stadium, France
Architects: Valode  Pistre and Ferret

Stainless steel mesh media facade.

The mesh supports a high power, versatile LED system which permits individually programmable lighting effects, ranging from simple graphics to video content.
Arenas References

11. Swimming Pools
Clockwise, from top left:
1. Olympic-size, stainless steel-lined swimming pool, Vichy, France
2. Custom stainless roof spa
3. Stainless steel handrail
Stainless Waterslide

Made from a single streamlined curve shape, the foot of the curve constitutes the steps that take the user to the top of the slide. The slide itself then loosens and turns in on itself. To create a contrast, the designers used a mirror-polished finish on the interior while the exterior is brushed.

"Polished stainless steel doesn’t get too hot to touch, even in sunny climates," the UK-based designers explained. "In fact, it actually reflects sunlight and thermal energy as it doesn't oxidise like other metals."
Swimming Pools References

Thank you

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 02B: Applications - Infrastructure
Contents

1. Water distribution
2. Bridges
3. Coastal Works
1. Water distribution
Why are stainless steels used?

- Low Leakage Rates: Stainless Steels do not suffer from uniform corrosion like their ductile iron or steel counterparts, which can result in the rupture and failure of pipelines. Stainless valves never seize. With proper design, stainless distribution can operate safely in earthquake-prone areas.
- Hygienic: Stainless Steels are basically inert in potable waters, which maintains water quality and drinking water integrity.
- Extended Service Life: Stainless steel components can provide 100 years of service due to their excellent corrosion resistance. They resist corrosion in most soils and do not require coatings or electrochemical protection systems.
- Recyclable: Unlike cement lined and non-metallic pipe, Stainless Steels are easily recycled and their alloy content is highly valued.
- Stainless is used for new large capacity reservoirs, new or for retrofitting existing ones.
Water leakage rate in some major cities (2014) ¹

Leakage rate in major cities
Source: OECD (Water Governance in Cities, 2014)
Reduction of leaks vs stainless steel pipe use in Tokyo\(^1\)

Reduction of leakage

- **Percentage of stainless steel pipes**
  - 1980: 69%
  - 2013: 100%

- **Leakage repair cases (’000)**
  - 1980: 15’000
  - 2013: 2’000

- **Leakage rate [% right]**
  - 1980: 1%
  - 2013: 2%
Reduction of water leakage with the replacement of old water pipes with stainless steel

Results of the projects in Tokyo, Seoul and Taipei

<table>
<thead>
<tr>
<th>Location</th>
<th>Leakage Rate 1980</th>
<th>Leakage Rate 2013</th>
<th>Leakage Volume 1980</th>
<th>Leakage Volume 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo</td>
<td>15.4%</td>
<td>2.1%</td>
<td>260 (Mil M³)</td>
<td>33 (Mil M³)</td>
</tr>
<tr>
<td>Seoul</td>
<td>27.3%</td>
<td>2.5%</td>
<td>502 (Mil M³)</td>
<td>29 (Mil M³)</td>
</tr>
<tr>
<td>Taipei</td>
<td>27.0%</td>
<td>16.7%</td>
<td>365 (Mil M³)</td>
<td>117 (Mil M³)</td>
</tr>
</tbody>
</table>
Water reservoir before repairs, Gangneung-City, Korea

The corrosion and deterioration of concrete is visible on the picture and causes water leakage. Epoxy coating was rejected as not lasting. Retrofitting with a Stainless steel lining was selected for corrosion resistance, durability, no maintenance and no bacterial growth.
Same after new stainless steel lining

Duplex Stainless steel Grades STS329LD and STS329J3L are used.

Panels are welded together and anchored into the concrete.
Water distribution References

5. Source: POSCO, Korea (http://www.posco.com)
2. Bridges
Many Bridges are in a poor condition

- A lot of them were built after World War 2
- For a projected life of 60 years plus
- Traffic has been heavier than planned
- Cutting maintenance costs has been a frequent practice
Situation in the European Union

- There is no comprehensive report published
- Varies from country to country
- Germany: 12.5 percent of Germany's motorway bridges are in good condition, while 12.4 percent are in poor condition
- France: a recent report concluded 1/3 of the bridges are in a bad condition
- etc...
The US Situation

Number of US bridges in need of replacement or rehabilitation, including structurally deficient bridges

<table>
<thead>
<tr>
<th>Year</th>
<th>Bridges in need of repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>244282</td>
</tr>
<tr>
<td>2015</td>
<td>235013</td>
</tr>
<tr>
<td>2016</td>
<td>229642</td>
</tr>
<tr>
<td>2017</td>
<td>238399</td>
</tr>
<tr>
<td>2018</td>
<td>234932</td>
</tr>
</tbody>
</table>
Stainless steel in bridges

Some examples
Stonecutter’s, Hong Kong

This heavily-trafficked iconic bridge is located in an urban area, and has been designed to withstand tropical weather conditions, urban pollution, sea mist, wind, typhoons, accidental loads due to ship impacts and seismic loading.

It was at the time (2009) the first cable-stayed bridge exceeding a 1km span and has an expected lifetime of 120 years. Duplex stainless steel UNS S32205 (EN1.4462) was used as skin around concrete for the upper part of the towers, for the cable-stay anchorage and for reinforcing bar of the foundations and lower parts of the towers.
Champlain, Montreal

The new bridge (2019), which replaces the old one that was failing due to corrosion, will resist severe freeze-thaw cycles with temperatures as low as -25°C to up to 30°C. It is 3.4km long, spans over the St. Lawrence river and the seaway and will carry over 50 millions vehicles per year. It features a 4-lane highway, a commuter rail line, bicycle tracks and lookouts for sightseeing. Over 15000T of stainless steel S32305 (EN1.4362) were used in the critical parts of the structure.

The old bridge opened in 1962. In spite of extensive maintenance it had to be replaced. The new bridge costs about 4200 Million CAD. In addition, de-construction of the old one will cost 400 Million CAD.
Hong Kong, Zhuhai, Macau

The bridge is a part of a 50km link consisting of a series of three cable stayed bridges, one 6.7 km undersea tunnel, and 3 artificial islands. The bridge was constructed over 9 years, at an estimated cost of $20 billion for a lifetime of 100 years and was completed in 2018.

Over 10000T of duplex stainless steel were used in the critical areas.
Fort Worth, Texas

This is the world’s first arch bridge made of precast elements, 12 in total and was completed in 2013. The innovative feature is the load-bearing angled hanger bars that connect the top and the bottom of the arch bridge. They provide stability and structural performance.

They are made of duplex stainless steel grade S32205 (EN1.4462). The overall design is structurally very efficient, very elegant and ensures long-term durability.
Cala Galdana, Menorca

This stainless steel bridge, commissioned in 2005, replaces a carbon steel reinforced concrete structure.

Duplex grade S32205 (EN1.4462) was selected over carbon steel for its higher mechanical properties and corrosion resistance. The minimum Yield strength specified was 460MPa, for a measured value of 535MPa, while the specified value for Carbon steel was only 355MPa.
Helix, Singapore

Its unique double helix structure, 280m long, supporting a walkway is made of tubes and plates of duplex S32205 (EN1.4462). This grade has been selected for its strength and corrosion resistance in a tropical maritime environment. The life cycle cost of the bridge will be lower than that of a carbon steel solution. The white light at night is particularly beautiful, enhanced by the surface finish of the stainless steel.
Lyon, France

Located in an area that underwent a major upgrading and close to the new Musée des Confluences, this duplex stainless steel pedestrian bridge opens up to allow the passage of ships entering the docks. It is elegant, aesthetic and requires no maintenance.
Trumpf, Germany

This footbridge over the heavily trafficked Gerlinger Strasse connects two work sites at the TRUMPF Headquarters in Ditzingen, Germany. Made of thin, strong, corrosion resistant duplex grades S32205 (EN1.4462) cut with TRUMPF laser technology, it has a very original shape that everyone remembers. It demonstrates that duplex is not for iconic structures only.
San Diego Harbor, California

This self-anchored suspension structure, 168m long, is strikingly beautiful. The curved deck is supported by stay cables attached to a single inclined pylon, resulting in a very simple and attractive design. Duplex stainless steel grade S31803 and austenitic 317L have been selected for structural parts, railings, cables and connectors. The expected life time will exceed 100 years in this marine environment.
Progreso Pier, Mexico

On the left, what remains of a pier which was built in 1970. The marine environment made the carbon steel rebar corrode – the structure failed.

On the right, the neighbouring pier erected in 1937 – 1941 using 304 stainless steel reinforcement which has been maintenance free and remained in pristine condition.
References on the condition of existing bridges

7. https://artbabridgereport.org/
8. https://www.infrastructurereportcard.org/cat-item/bridges/
References on bridges with stainless steel


5. N. Baddoo and A. Kosmač “Sustainable Duplex Sainless Steel bridges” Euro Inox publication  [www.worldstainless.org/Files/issf/non-image-files/PDF/Sustainable_Duplex_Stainless_Steel_Bridges.pdf](www.worldstainless.org/Files/issf/non-image-files/PDF/Sustainable_Duplex_Stainless_Steel_Bridges.pdf)

References on bridges with stainless steel

https://www.researchgate.net/publication/233611421_Stonecutters_Bridge_-_Detailed_Design/link/59ce24d3aca272b0ec1a4b34/download


https://www.researchgate.net/publication/233632633_Use_of_Duplex_Stainless_Steel_Plate_for_Durable_Bridge_Construction


11. Champlain bridge, Montreal Stainless Steel World online, 05 January 2016

12. Hong-Kong Macau bridge ISSF Publication: “Stainless steel in Infrastructure”
https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_in_Infrastructure_English.pdf
References on bridges with stainless steel

13. Hong-Kong Macau bridge
   https://en.wikipedia.org/wiki/Hong_Kong%E2%80%93Zhuhai%E2%80%93Macau_Bridge

14. IMOA publication “Innovative bridge at Ft Worth, Texas” Moly-Review 1/2018
    https://www.imoa.info/molybdenum-media-centre/downloads/

    http://www.worldstainless.org/architecture_building_and_construction_applications/structural_applications

16. Railways Bridges in India


18. ISSF Publication: Bascule pedestrian bridge in “Stainless steel as an architectural material”
    https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_as_an_Architectural_Material.pdf

19. Trumpf bridge

20. IMOA Publication “San Diego’s new harbor bridge sails onto the skyline” MolyReview, (June2012)
3. Coastal Infrastructure

37% of the world’s population lives within 100km of the coast
Climate change and coasts

A few consequences:

- Oceans are rising at a rate of about 3mm/year...and will not go back! Some land is already/will be flooded

- Extreme meteorological events are more frequent (such as class 5 hurricanes, super typhoons...), adding to coastal damage

- Major changes on coastal ecosystems, mostly destruction, are taking place

- Human populations and activities are threatened with a huge human and economic cost.
Flooding (Southwest France)
Coastal damage (location unknown)
Coastal adaptation options

- Managed retreat (e.g. movable structures, inland flood defences, flood warning systems)
- Accommodation (e.g. reservoir relocation, dune management, rain/waste-water management)
- Protection (includes a wide array of technologies available to coastal engineers to stabilize a coastline, including soft technologies such as beach nourishment as well as hard structures such as sea walls, revetments, groynes)

Source: www.unfccc.int/resource/docs/tp/tp0199.pdf
https://www.unenvironment.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/coastal-zone-management
Some structures for protection that use stainless steel
Sea Wall, Cromer, UK

Cromer is a beautiful North Norfolk seaside resort from the Victorian times. Protection against the sea is achieved by a concrete sea wall and by timber groynes. Following a major storm in 2013, large and expensive repairs had to be carried out, not only to maintain the actual level of defense, but also to anticipate 100 years of predicted sea level rise.

In this project, over 300 MT of S32304 (EN1.4362) duplex stainless steel rebar were used.
Breakwater, Bayonne, France

The breakwater, built in the 1960s, protects the entrance of the Bayonne harbor against storms. It features a wall and a platform wide and strong enough to bear a heavy duty crane. This crane replaces the 40T concrete blocks that dissipate the energy of the incoming waves on the sea side as they wear out.

As the platform itself eventually started to show cracks, it has been repaired using high strength S32205 (EN1.4462) duplex stainless steel rebar (Yield stress min 750Mpa), allowing a significant reduction of tonnage. In the end only 130 Tons of rebar were needed.
Safety measures in Japan

Contribution to reconstruction of the disasters and the national resilience
The number of deaths caused by the Great East Japan Earthquake in March 2011 was approximately 16,000, and more than 90% of those killed by tsunami, which was exceptionally large. After the Earthquake, Japanese Government changed the specification of the height of the water gates from 5m to 8m. This upsizing led the increase of water pressure and it was required to increase the strength of the gates with additional the design. Solution: NIPPON STEEL Stainless Steel Corporation proposed Alloy-Saving Duplex Stainless Steel (ASDSS), which enabled reducing its weight and simplifying the design by its strength.

Source: NIPPON STEEL Stainless Steel Corporation
Examples of water gates in Japan

Slide gate
Height: 8.2 m x Width 15 m

Water gate
Height: 6.2 m x Width 15 m

Source: NIPPON STEEL Stainless Steel Corporation
Weight reduction of water gates achieved by Lean Duplex stainless steel

Design comparison (dam discharging gate 7m x 7.8m = 54.6m²)

Source: Electric power civil engineering (2016.9)
Some of the major projects in Japan

- ASDSS is used for more than 50 Dams and Water Gates in Japan, especially for the Earthquake Reconstruction Project.
Kamihirai gate, Japan

A view of the gate being built
Mont Saint Michel, France
Mont Saint Michel, France

- Mont Saint Michel is one of the most visited tourist spots of France. The tiny island with its cloister and with an angel on top is located in a bay. Over time, stilting of the bay was slowly taking place, changing the landscape.

- Gates were built to store the water of the incoming stream during the incoming tides and release it at low tides, thereby taking away some sediments back to the sea twice per day. The eight sets of sluice gates clad were built using 36 T of S32205 (EN 1.4462) duplex stainless steel, selected for its good corrosion and abrasion resistance.

- Mont Saint Michel now returns to the sea.
Monaco Extension over the sea

The Principauté (principalty) de Monaco, on the Mediterranean coast, is expanding its tiny territory (2km²) over the sea to build a huge 600 000m² new city development, for an estimated cost of 2 billion Euros.

The technical challenges are huge: creating a temporary dam to build the enclosure; erecting the concrete wall capable of lasting at least 100 years, filling up the new space gained over the sea and preparing it for multi storey residential buildings, minimizing the impact on marine life, etc.

Over 4000MT of duplex S32304 (EN1.4362) stainless steel rebar will be used to reinforce the concrete walls and protect them against the corrosion by sea water.
References

1. https://www.ipcc.ch/
2. www.unfccc.int/resource/docs/tp/tp0199.pdf
7. Sea Wall at Cromer  http://www.stainlesssteelrebar.org/applications/coastal-protection-at-cromer-uk/
10. Tsunami-proof floodgates Japan (NSSC presentation)
References

11. Sluices Mt St Michel
   https://europe.arcelormittal.com/europeprojectgallery/fol_montsaintmichel

12. Tammeroski floodgate
    https://www.pontek.fi/in-english

13. Monaco

14. Gårda Dämme floodgate, Göteborg

Waves construct and destruct the coastlines

Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 03

Why stainless steels?
Introduction

Main materials used in architecture, building and construction
## Relative use of the main building materials today

<table>
<thead>
<tr>
<th>Materials</th>
<th>World Production *</th>
<th>Average Density</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rammed earth, <em>pisé</em></td>
<td>na</td>
<td></td>
<td>Was used for traditional houses in Africa mostly. Some renewed interest for its environmental properties</td>
</tr>
<tr>
<td>Bricks</td>
<td>4185</td>
<td>2,0</td>
<td>Year 2017</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Of which 87% in Asia</td>
</tr>
<tr>
<td>Cement</td>
<td>3545</td>
<td>2,4**</td>
<td>(To obtain the figure for concrete multiply by 3-4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>**Concrete density - 2018 figures</td>
</tr>
<tr>
<td>Steel</td>
<td>1690</td>
<td>7,8</td>
<td>(Crude Steel production 2018) –Includes stainless steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14% goes into infrastructures - half as rebar 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>42% goes into buildings 12</td>
</tr>
<tr>
<td>Cast Iron and Steel</td>
<td>110</td>
<td>7,8</td>
<td>2017 Figures</td>
</tr>
<tr>
<td>Wood</td>
<td>887</td>
<td>0,56</td>
<td>Sawn wood+wood-based panels only (2016 figures)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Excluding pulpwood (about 656)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Excluding wood fuel (1860) &amp; other wood products</td>
</tr>
<tr>
<td>Man-Made Polymers</td>
<td>348</td>
<td>1,1</td>
<td>Some Natural Polymers: Cellulose, Rubber, Silk, Chitin 2017 figures</td>
</tr>
<tr>
<td>Man-made Glass</td>
<td>75</td>
<td>2,6</td>
<td>Flat glass only (80% of total glass market) 2018 figures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Main other markets: Automotive, Solar energy Glass</td>
</tr>
<tr>
<td>Aluminum</td>
<td>64</td>
<td>2,7</td>
<td>(Primary Aluminum Production in 2018)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24% goes into construction 10</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>51</td>
<td>7,8</td>
<td>2018 figures 17% goes into construction</td>
</tr>
</tbody>
</table>

na: not available

* in Millions Metric Tons

**Concrete density - 2018 figures

---

**Updated 2019**
Young’s modulus $E$ of various materials\(^{12}\) (stiffness)

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus $E$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steels</td>
<td>~210</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>~210</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>~130</td>
</tr>
<tr>
<td>Titanium Alloys</td>
<td>~100</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>~70</td>
</tr>
<tr>
<td>Concrete</td>
<td>~40</td>
</tr>
<tr>
<td>Wood</td>
<td>~10</td>
</tr>
<tr>
<td>Plastics</td>
<td>~4</td>
</tr>
</tbody>
</table>

Stainless steels are as stiff as steel
Stainless steels offer a strength/weight ratio comparable to steels and to Al alloys.

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength (YS)/Specific Weight</th>
<th>Yield, Stress, Mpa</th>
<th>Ultimate Tensile Strength, Mpa</th>
<th>Specific wt (Kg/dm³)</th>
<th>Min Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless 304 or 316, annealed</td>
<td>26</td>
<td>205</td>
<td>515</td>
<td>7,8</td>
<td>35</td>
</tr>
<tr>
<td>Stainless 304 or 316, work-hardened CP 350</td>
<td>45</td>
<td>350</td>
<td>-</td>
<td>7,8</td>
<td>-</td>
</tr>
<tr>
<td>Stainless 304 or 316, work-hardened CP 500</td>
<td>62</td>
<td>480</td>
<td>-</td>
<td>7,8</td>
<td>-</td>
</tr>
<tr>
<td>Duplex 2205</td>
<td>64</td>
<td>500</td>
<td>700/950</td>
<td>7,8</td>
<td>20</td>
</tr>
<tr>
<td>Stainless 630, aged</td>
<td>103</td>
<td>800</td>
<td>950/1150</td>
<td>7,8</td>
<td>10</td>
</tr>
<tr>
<td>C-steel commercial sheet, Hot rolled</td>
<td>30</td>
<td>234</td>
<td>317</td>
<td>7,8</td>
<td>35</td>
</tr>
<tr>
<td>Structural Steel (plate and bar)</td>
<td>32</td>
<td>250</td>
<td>400/550</td>
<td>7,8</td>
<td>23</td>
</tr>
<tr>
<td>HSLA Steel</td>
<td>49</td>
<td>380</td>
<td>460</td>
<td>7,8</td>
<td>25</td>
</tr>
<tr>
<td>Engineering Steel 4140 Q&amp;T</td>
<td>96</td>
<td>750</td>
<td>930/1080</td>
<td>7,8</td>
<td>12</td>
</tr>
<tr>
<td>Aluminum Alloy 3003- H14</td>
<td>37</td>
<td>145</td>
<td>150</td>
<td>2,7</td>
<td>40</td>
</tr>
<tr>
<td>Aluminum Alloy 3105- H14</td>
<td>38</td>
<td>150</td>
<td>170</td>
<td>2,7</td>
<td>5</td>
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<tr>
<td>Aluminum Alloy 5005- H16</td>
<td>44</td>
<td>170</td>
<td>180</td>
<td>2,7</td>
<td>5</td>
</tr>
<tr>
<td>Aluminum Alloy 6061- T6</td>
<td>71</td>
<td>275</td>
<td>310</td>
<td>2,7</td>
<td>12</td>
</tr>
<tr>
<td>Aluminum Alloy 6063- T5</td>
<td>37</td>
<td>145</td>
<td>185</td>
<td>2,7</td>
<td>12</td>
</tr>
<tr>
<td>Copper</td>
<td>23</td>
<td>195</td>
<td>250</td>
<td>8,3</td>
<td>30</td>
</tr>
</tbody>
</table>
# Simplified overview of different materials

<table>
<thead>
<tr>
<th>Properties</th>
<th>EN 1.4521 AISI 444</th>
<th>EN 1.4301 AISI 304</th>
<th>EN 1.4401 AISI 316</th>
<th>Copper</th>
<th>Aluminum</th>
<th>Carbon Steel</th>
<th>Plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>- -</td>
<td>+</td>
<td>-</td>
<td>+ +</td>
</tr>
<tr>
<td>Linear expansion</td>
<td>+ +</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>- -</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>- -</td>
<td>-</td>
<td>-</td>
<td>+ + +</td>
<td>+</td>
<td>0</td>
<td>- -</td>
</tr>
<tr>
<td>Ferromagnetism</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness (Young's modulus)</td>
<td>+ + +</td>
<td>+ + +</td>
<td>+ + +</td>
<td>+</td>
<td>-</td>
<td>+ + +</td>
<td>- -</td>
</tr>
<tr>
<td>Tensile</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>+ / + +</td>
<td>-</td>
</tr>
<tr>
<td>Elongation</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>0</td>
<td>- / + +</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fabrication</td>
<td>+ +</td>
<td>+ +</td>
<td>+ +</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>High temperatures</td>
<td>+ +</td>
<td>+ +</td>
<td>+ + +</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>- -</td>
</tr>
<tr>
<td>Low temperatures</td>
<td>-</td>
<td>+ + +</td>
<td>+++</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>+ + +</td>
<td>+++</td>
<td>++++</td>
<td>+ +</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Symbols: + Advantage - Weakness (relative to the other materials)
Stainless steel remains a « young » material
New materials have appeared in the course of history
Stainless steel is the most recent*

<table>
<thead>
<tr>
<th>Materials</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rammed earth, <em>pisé</em></td>
<td>Has been used since the dawn of mankind!</td>
</tr>
<tr>
<td>Wood</td>
<td>Has been used since the dawn of mankind!</td>
</tr>
<tr>
<td>Brick</td>
<td>7500 BC 4500 BC</td>
</tr>
<tr>
<td></td>
<td>Fired bricks/ceramics</td>
</tr>
<tr>
<td>Steel</td>
<td>4000 BC 1858</td>
</tr>
<tr>
<td></td>
<td>Blacksmiths’ shops</td>
</tr>
<tr>
<td></td>
<td>Bessemer Process</td>
</tr>
<tr>
<td>Man-made Glass</td>
<td>3500 BC 100 BC 1950</td>
</tr>
<tr>
<td></td>
<td>First glassmaking</td>
</tr>
<tr>
<td></td>
<td>Clear Glass</td>
</tr>
<tr>
<td></td>
<td>Pilkington (Float Glass) Process</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1825 1885</td>
</tr>
<tr>
<td></td>
<td>Oersted discovers Aluminum</td>
</tr>
<tr>
<td></td>
<td>The Hall –Heroult process</td>
</tr>
<tr>
<td>Reinforced Concrete</td>
<td>1850 1885</td>
</tr>
<tr>
<td></td>
<td>But cement is much older</td>
</tr>
<tr>
<td></td>
<td>Rotary Kiln Process</td>
</tr>
<tr>
<td>Man-Made Polymers</td>
<td>1846 1907 1939</td>
</tr>
<tr>
<td></td>
<td>Celluloïd</td>
</tr>
<tr>
<td></td>
<td>Bakelite</td>
</tr>
<tr>
<td></td>
<td>Nylon</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>1912-1913 1954 1955</td>
</tr>
<tr>
<td></td>
<td>Early alloys</td>
</tr>
<tr>
<td></td>
<td>AOD Process</td>
</tr>
<tr>
<td></td>
<td>Hot Strip Rolling</td>
</tr>
</tbody>
</table>

* There are newer materials, of course, but not used in significant quantities
Why stainless steels?

Demand keeps growing

World Stainless Steel Production by area

- 2012: 35,917
- 2013: 38,506
- 2014: 41,686
- 2015: 41,545
- 2016: 45,448
- 2017: 48,081
- 2018: 50,729

UPATED 2019!
Compound annual growth of world Stainless Steel meltshop production (Millions of Metric tons)

Compound annual growth: 5.84%
Why Stainless steel?
Because of an outstanding set of properties

1. **Corrosion resistance** (see chapter 3)
   - In all environments: tropical to polar, sea or desert, polluted or not...
   - Self-repairing, unlike coatings

2. **Lasting forever** with little or no maintenance

3. **Wide range of mechanical properties** allowed by several stainless families (Cr-Ni Austenitics – Cr-Mn Austenitics – Cr Ferritics – Duplex – Cr C Martensitics) and now built into the major building codes. Plus an excellent fire resistance (see Chapters 4 and 5)

4. **Aesthetics**: Large selection of surface finishes à colors available (see chapter 6). Plus resistance to damage in public areas

5. **Easy fabrication/joining** (see chapter 7)

6. **Excellent sustainability** (see chapter 9)
   - allows a long service life with no or little maintenance,
   - 100% recyclable (and more than 85% recycled) at the end of life into stainless steel without loss of properties

7. **Safe and Hygienic**: Inert, no contamination, easy to clean & disinfect

8. **Specific properties**: magnetic/non magnetic, ....
What limits the use of stainless steels: the price

Stainless Steels are expensive: True? Or False?

Answer: Yes and No

Yes:
If the initial material cost is all what matters (usually because of limited funding...)
But then a bad choice may be very expensive:
- Stainless steel usually represents a small part of the project
- Untimely repairs and maintenance may add huge direct and indirect costs

No:
if
- the Life Cycle Cost (the « real » cost) is taken into account, i.e. if maintenance, service life and recycling issues are factored in*
- the design is optimized: thin sheets, profiled into complex shapes can result, in strong, stiff structures that use little material.

*The owner’s best interest is always to make choices based on LCC analysis
Stainless (and other metals) use less material\textsuperscript{16}

Thin gauge 0,4mm and 0,6mm thick stainless steel sheets are commonly used. Weight: 3,12Kg and 4,68Kg respectively per m\textsuperscript{2} only!
Why stainless steel is not expensive if the life cycle cost is taken into account

The cost of structures made of other materials substantially increases over time while the cost of stainless steel structures normally remains constant.

The Cost of corrosion exceeds 276 Billions $ in the USA alone.
## Life Cycle Cost Comparison of 2 old structures

<table>
<thead>
<tr>
<th>Structures</th>
<th>Completed</th>
<th>Material</th>
<th>Height</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eiffel Tower – Paris *</td>
<td>1889</td>
<td>Wrought iron</td>
<td>324m</td>
<td>Every 7 years. Every painting campaign lasts for about a year and a half (15 months). 50 to 60 tons of paint, 25 painters, 1500 brushes, 5000 sanding disks and 1500 sets of work clothes.</td>
</tr>
</tbody>
</table>

* The Eiffel tower was built before stainless steel was invented...and it was supposed to be a temporary structure, but the public loved it!
Example:
Comparison of the maintenance of 2 very well known bridges\textsuperscript{20, 21}

- Golden Gate Bridge in San Francisco
- Stonecutter’s Bridge in Hong Kong

In the next 2 slides
The Golden Gate bridge (1937), San Francisco

“a rugged group of 13 ironworkers and 3 pusher ironworkers along with and 28 painters, 5 painter laborers, and a chief bridge painter battle wind, sea air and fog, often suspended high above the Gate, to repair corroding steel. Ironworkers replace corroding steel and rivets with high-strength steel bolts, make small fabrications for use on the Bridge, and assist painters with their rigging. Ironworkers also remove plates and bars to provide access for painters to the interiors of the columns and chords that make up the Bridge. Painters prepare all Bridge surfaces and repaint all corroded areas.” 20
Project details: 1,596m-long dual 3-lane high-level cable-stayed bridge, with a clear span of 1,018m. Typhoon resistant.

Material: Stainless Steel EN1.4462 (Duplex) plate with 450MPa yield stress used for the towers above +175m to top (+295m) and for towers skin.

Why stainless rather than C-steel: designed for 120 years life in a hot and polluted seawater environment. Designed for no maintenance.\(^{21}\)
Main references

1. https://worldstainless.org/
2. (a) http://www.hablakilns.com/the-brick-industry/the-brick-market/
   (b) http://wiki.answers.com/Q/What_is_the_weight_of_a_red_clay_brick_in_Kilograms
4. (a) https://www.worldsteel.org/ (b) www.globalcastingmagazine.com
15. Wikipedia
Main references (Cont’d)

17. US Federal Highway administration reports FHWA-RD-01-156 and 157  www.corrosioncost.com
Thank you

Test your knowledge of stainless steel here:
https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 04

What are the stainless steels?
What are stainless steels?

Videos

100 Years of Stainless Steel
https://youtu.be/E-GcuxtWcnc

Alloyed for Lasting Value
https://youtu.be/l4Z1UVWm3DE

Self-repairing for Lasting Value
https://youtu.be/ngnT6dYo-M0
Stainless steels are Iron-base alloys containing at least 10.5% chromium

Increasing Cr content increases the effectiveness of the passive film... but there are other important factors that influence the corrosion resistance (see Chapter 5)
What are stainless steels?

Stainless steels are a type of steel that contain chromium and nickel. They are known for their resistance to rust and corrosion.

**Martensitic**
- Plain chromium stainless steels that can be strengthened by heat treatment.
- 10-17%Cr
- 0.1-1.2%C
- 0-4%Ni

**Ferritic**
- Plain chromium stainless steels, but with low carbon levels, therefore cannot be strengthened by heat treatment.
- Generally considered to have poor weldability with the exception of the utility grades.

**Duplex**
- Mixed ferrite-austenitic crystal structure (duplex)
- Higher levels of Cr and lower levels of Ni as compared to the austenitic grades. Contain nitrogen.
- High strength and good corrosion resistance. Weldable

**Austenitic**
- Ni containing stainless steels. Most common grades which account for 70% of all stainless steel usage.
- Excellent corrosion resistance and associated secondary properties. Suitable for a wide range of applications.

The properties of stainless steels can be adjusted by adding carbon and nickel.

- **Martensitic structure**: Add carbon
- **Ferritic structure**: Add nickel
- **Duplex structure**: Add more nickel
- **Austenitic structure**: Add nickel

**Plain chromium (Cr)**: 10-17%

**Nickel (Ni) addition**: 0.1-1.2%

**Iron (Fe) + Chromium (Cr)**: 0-4%
## Cr-Ni Grades (Austenitics)⁴

### Sub-groups:

<table>
<thead>
<tr>
<th>Sub-group</th>
<th>Composition</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr-Ni</td>
<td>EN 1.4301/AISI 304</td>
<td>Very good corrosion resistance, increases with alloy content.</td>
</tr>
<tr>
<td>Cr-Ni-Mo</td>
<td>EN 1.4401/AISI 316</td>
<td>High ductility and impact resistance at all (including very low) temperatures.</td>
</tr>
</tbody>
</table>

### Common Properties:

- Very good corrosion resistance, increases with alloy content.
- High ductility and impact resistance at all (including very low) temperatures.
- Strength can be increased by cold working (but not by heat treatment).
- Very good fire resistance.
- Very good cold and hot forming properties (ductility, elongation).
- Easy to weld (TIG, MIG).

The best known and still the most used today.
Cr-Mn Grades (Austenitics with Manganese)\textsuperscript{5}

**Typical grade:**
- Cr-Mn-Ni-N  Typically EN 1.4372/AISI 201  Cr: 17  Mn: 7  Ni: 4  N:0.15  Fe: Balance

**Common Properties:**
- Lesser corrosion resistance
- ... but far more susceptible to SCC and to pitting, particularly at low Ni and Cr levels
- Higher strength
- Poor cold forming properties due to high work-hardening
- Poor machinability
- More difficult to weld
- Cost less than Cr-Ni Austenitics ... but more than Cr ferritics

Used mostly in India and China
**Cr Grades (Ferritics)**

<table>
<thead>
<tr>
<th>Sub-groups</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>Typically EN 1.4016/AISI 430 Cr: 17 Fe: Balance</td>
</tr>
<tr>
<td>Cr-Mo</td>
<td>Typically EN1.4521/AISI 444 Cr: 18 Mo: 2 Ti+Ni: 0.4 Fe: Balance</td>
</tr>
</tbody>
</table>

**Common Properties:**

- Insensitive to Stress Corrosion Cracking
- Good ductility (lower than austenitic grades, though)
- Not suitable for use at very low temperatures
- Strength can be somewhat increased by cold working (but not by heat treatment)
- Very good cold forming properties: (less springback, lower tool wear but lower elongation requires a different deep drawing process compared to austenitics)
- Stabilized grades (i.e. with Nb and/or Ti) are easy to weld (TIG, MIG)

*Offer an optimum performance/cost for many applications and are increasingly used*
Cr Grades (Martensitics)\(^7\)

<table>
<thead>
<tr>
<th>Sub-groups:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C-Cr</td>
<td>Typically EN1.4021/AISI 420</td>
<td>Cr: 13</td>
<td>C: 0.2</td>
</tr>
<tr>
<td>C-Cr-Ni</td>
<td>Typically EN1.4057/AISI431</td>
<td>Cr: 16</td>
<td>Ni: 2</td>
</tr>
<tr>
<td>Precipitation Hardening</td>
<td>Typically EN1.4542/AISI630</td>
<td>Cr: 17</td>
<td>Ni: 4</td>
</tr>
</tbody>
</table>

**Common Properties:**

- Fair to good corrosion resistance, increases with alloy content
- High strength obtained by heat treatment (not by cold work). Limited elongation.
- Not suitable for use at very low temperatures
- Not suitable for forming, often processed by machining
- Can be welded (TIG, MIG), but require usually post-weld heat treatment

Colour code:

- Corrosion resistance
- Mechanical properties
- Fabrication

**Are used as engineering steels with corrosion resistance**
Duplex (Austenitic-Ferritic)

Sub-groups:

- **Cr-Ni**  
  Typically EN1.4362  
  Cr: 23  Ni: 4  Fe: Balance

- **Cr-Ni-Mo**  
  Typically EN1.4462  
  Cr: 22  Ni: 5  Mo: 3  Fe: Balance

**Common Properties:**

- Excellent corrosion resistance, increases with alloy content
- Insensitive to Stress Corrosion Cracking
- High strength, good ductility
- Strength can be increased by cold working (but not by heat treatment)
- Good cold and hot forming properties (ductility, elongation)
- Weldable (TIG, MIG)

**Offer the best combination of corrosion resistance and mechanical properties**
Physical properties\textsuperscript{9, 10}

<table>
<thead>
<tr>
<th>Materials</th>
<th>Modulus of Elasticity Gpa</th>
<th>Thermal Expansion Coefficient $10^{-6}°K^{-1}$</th>
<th>Thermal Conductivity W m$^{-1}°K^{-1}$</th>
<th>Ferro-Magnetism</th>
<th>Density Kg/dm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr-Ni Austenitics</td>
<td>210</td>
<td>18</td>
<td>15</td>
<td>No</td>
<td>7.8</td>
</tr>
<tr>
<td>Cr-Mn Austenitics</td>
<td>210</td>
<td>17</td>
<td>15</td>
<td>No</td>
<td>7.8</td>
</tr>
<tr>
<td>Cr Ferritics</td>
<td>220</td>
<td>11</td>
<td>23</td>
<td>Yes</td>
<td>7.7</td>
</tr>
<tr>
<td>Cr-Ni (Mo)-N Duplex</td>
<td>210</td>
<td>14</td>
<td>15</td>
<td>Intermediate</td>
<td>7.8</td>
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<tr>
<td>Cr-C Martensitics</td>
<td>215</td>
<td>11</td>
<td>30</td>
<td>Yes</td>
<td>7.7</td>
</tr>
<tr>
<td>Carbon Steel</td>
<td>210</td>
<td>12</td>
<td>18</td>
<td>Yes</td>
<td>7.8</td>
</tr>
<tr>
<td>Copper</td>
<td>135</td>
<td>17</td>
<td>380</td>
<td>No</td>
<td>8.3</td>
</tr>
<tr>
<td>Aluminum</td>
<td>70</td>
<td>22</td>
<td>230</td>
<td>No</td>
<td>2.7</td>
</tr>
<tr>
<td>Glass</td>
<td>65</td>
<td>9</td>
<td>1.7</td>
<td>No</td>
<td>2.5</td>
</tr>
<tr>
<td>Concrete</td>
<td>48</td>
<td>10</td>
<td>1</td>
<td>No</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Standards on Stainless Steels

Main World Standards:

ISO | EN | ASTM/AISI | UNS | JIS

Notes:
Most countries refer to the above standards, which are widely accepted. A lot of the grades are very similar in all of the above standards.

List of the American Standards: ref 11
List of European Standards: ref 12

Correspondance tables are available: refs 13 - 15
What are stainless steels?

Main grades in Architecture Building and Construction:
EN 10088-4 (for sheet/plate/strip)\(^{16, 17}\)

<table>
<thead>
<tr>
<th>Grade</th>
<th>ASTM UNS</th>
<th>C Wt%</th>
<th>Cr Wt%</th>
<th>Ni Wt%</th>
<th>Mo Wt%</th>
<th>Other Wt%</th>
<th>Typical use (^{3,4})</th>
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</thead>
<tbody>
<tr>
<td>4003</td>
<td>S40977</td>
<td>0,02</td>
<td>11,5</td>
<td>0,5</td>
<td>-</td>
<td>-</td>
<td>heated and unheated interiors</td>
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<tr>
<td>4016</td>
<td>430</td>
<td>0,04</td>
<td>16,5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>decorative interior cladding</td>
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<tr>
<td>4509</td>
<td>S43932</td>
<td>0,02</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>Nb Ti Ti</td>
<td>inland roofing and rainwater goods - often Tin-coated for patina</td>
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<tr>
<td>4510</td>
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<td>4521</td>
<td>444</td>
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<td>-</td>
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<td>Ti</td>
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<tr>
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<td>-</td>
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<tr>
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<td>316</td>
<td>0,04</td>
<td>17,2</td>
<td>10,1</td>
<td>2,1</td>
<td>Ti</td>
<td>permanently wet applications, locations in a coastal atmosphere, polluted industrial atmospheres or near roads where de-icing salts can be an issue</td>
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<td>24,8</td>
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<td>N, Cu N, Cu</td>
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<td>6,1</td>
<td>-</td>
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</table>

ABC = Architecture, Building and Construction
Main grades in Architecture Building and Construction: EN 10088-5(for bars/wires/sections)\textsuperscript{18}

<table>
<thead>
<tr>
<th>Grade</th>
<th>ASTM UNS</th>
<th>C Wt%</th>
<th>Cr Wt%</th>
<th>Ni Wt%</th>
<th>Mo Wt%</th>
<th>Other Wt%</th>
<th>Typical use \textsuperscript{6}</th>
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<td>-</td>
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<tr>
<td>4016</td>
<td>430</td>
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<td>16,5</td>
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<td>-</td>
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<td>Slate hooks</td>
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<td>4542</td>
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<td>4,0</td>
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<td>Tie bars</td>
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<td>-</td>
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<td>8,1</td>
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<td>-</td>
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<tr>
<td>4311</td>
<td>304N</td>
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<td>18,1</td>
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<td>-</td>
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<td>Rebar</td>
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<td>Cu</td>
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<td>2,1</td>
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<td>Rebar</td>
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<td>0,01</td>
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<td>24,8</td>
<td>6,5</td>
<td>N, Cu</td>
<td>Road tunnels and indoor swimming pools</td>
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<td>4547</td>
<td>S31254</td>
<td>0,01</td>
<td>20,0</td>
<td>18,0</td>
<td>6,1</td>
<td>N, Cu</td>
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<td>N, Cu</td>
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<td>4,6</td>
<td>2,8</td>
<td>N</td>
<td>Rebar and mechanical components</td>
</tr>
</tbody>
</table>
Breakdown of the stainless steel production worldwide by family
High Ni prices favour the replacement of popular CrNi grades by Cr-Mn or Cr Grades. Duplex grades marginal today, are expected to grow in the future.
What are stainless steels?

World stainless meltshop production (slab/ingot equivalent)

- USA:
- China:
- Europe:
- Asia without China and Korea:
- Others:
Apparent stainless use by region

What are stainless steels?
References (1/2)

4. New « 200 series steels »: An opportunity or a threat to the image of stainless steel? 
What are stainless steels?

References (2/2)


Thank you!

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 05: Corrosion Resistance of Stainless Steels
Contents

1. Most materials decay over time
2. Why does stainless steel resist corrosion
3. Types of corrosion of stainless steels
4. How to select the right stainless steel for adequate corrosion resistance
   - Structural applications
   - Other applications
5. References
1. Most materials decay over time
Most materials decay over time

<table>
<thead>
<tr>
<th>Material</th>
<th>Wood</th>
<th>Steel</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of decay</td>
<td>Fungi</td>
<td>Rust</td>
<td>Cracking/Spalling</td>
</tr>
<tr>
<td></td>
<td>Insects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sun+rain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitigating actions</td>
<td>Chemicals</td>
<td>Galvanising</td>
<td>Corrosion resistant</td>
</tr>
<tr>
<td></td>
<td>Paint/varnish</td>
<td>Painting</td>
<td>rebar</td>
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</table>
Most materials decay over time

<table>
<thead>
<tr>
<th>Material</th>
<th>Stone</th>
<th>Glass</th>
<th>Polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of decay</td>
<td>Wear Damage by Pollution</td>
<td>Breaks</td>
<td>Become brittle under UV light</td>
</tr>
<tr>
<td>Mitigating actions</td>
<td>Usually none taken</td>
<td>Tempered glass</td>
<td>Improved polymer grades</td>
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</tbody>
</table>
## Most materials decay over time

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminum*</th>
<th>Copper</th>
<th>Stainless</th>
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</thead>
<tbody>
<tr>
<td>Type of decay</td>
<td>Pitting over time, possible galvanic corrosion</td>
<td>Forms a green patina over time</td>
<td>No decay</td>
</tr>
<tr>
<td>Mitigating actions</td>
<td>Galvanic corrosion can be prevented</td>
<td>None</td>
<td>None required</td>
</tr>
</tbody>
</table>

* Aluminum forms a thin protective oxide just like stainless, but with a much lower corrosion resistance*
Corrosion in concrete  
(corrosion problems are not limited to outside surfaces !)

- Corrosion of unprotected carbon steel occurs even inside reinforced concrete structures as chlorides present in the environment (marine/deicing) diffuse through the concrete.
- Corrosion products (rust) have a higher volume than the metal, create internal tensions causing the concrete cover to spall.
- Mitigating the corrosion of steel reinforcing bar in concrete is a must.
- Various techniques are used: thicker concrete cover; cathodic protection; membranes, epoxy coating ... and stainless steel rather than C-Steel.

Stainless steel provides both strength and corrosion resistance inside the concrete, providing a long, maintenance-free service life of the structure.
2. Why does stainless steel resist corrosion
Passive Layer vs. Coatings

PASSIVE FILM on STAINLESS STEEL: Oxy-hydroxides of Fe and Cr

MILD STEEL

- Topcoat
- Coat
- Primer

MULTI-LAYER COATINGS

- Typically 20-200 µm thick
- May peel off
- Not self-repairing

Oxygen

2-3 nm thick (0.002-0.003 µm)

Transparent
Adherent
Self repairing
Damage to protective layer

Stainless Steel
- Passive film
- Self Repair

Mild Steel
- Multi-layer Coating
- Corrosion Products
3. Types of corrosion of stainless steels
Effect of Chromium Content on Atmospheric Corrosion Resistance (uniform corrosion)

Corrosion Rate

mmpy
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025

% Chromium
0 2 4 6 8 10 12 14 16

Plain Carbon Steel

Stainless Steels
> 10.5 Cr %
When the selection of the stainless steel grade has not been properly made, corrosion may occur...

...no material is perfect!

think of it as selecting the right vehicle for the intended use
Types of corrosion on stainless steels

a) Uniform
b) Pitting
c) Crevice
d) Galvanic
e) Intergranular
f) Stress corrosion cracking

See Reference 1
a) What is uniform corrosion?

- When the passive film is destroyed by the aggressive environment, the whole surface corrodes uniformly and metal loss can be expressed as µm/year
- This is typical of unprotected Carbon steels.
- This does not occur on stainless steels in the building industry, as the corrosion conditions are never that aggressive (it requires typically immersion in acids)
b) What is pitting corrosion\(^1,2,3,7\)?

Pitting corrosion, or pitting, is a form of extremely localized corrosion that leads to the creation of small holes in the metal.

This picture shows pitting of stainless steel EN1.4310 (AISI 301) resulting from insufficient corrosion resistance in a very aggressive chlorinated environment.
Pitting corrosion mechanisms

1. Initiation on a very small surface irregularities or non-metallic inclusions

2. Propagation as the electrochemical reactions in the pit cavity are not prevented by re-passivation
Pitting can be reproduced in an electrochemical cell\textsuperscript{4}

- Corrosion involves the dissolution of metal, i.e. an electrochemical process with
  a) electrochemical reactions at the surface of the metal and
  b) a current between the corroding metal (anode) and a cathodic part
- These processes can be simulated in an electrochemical cell, a device that allows the study of corrosion processes
Major factors that influence pitting corrosion
(the pitting potential $E_{\text{pit}}$ is generally used as the criterion for pitting)

1. Temperature

Increasing the temperature reduces drastically the resistance to pitting.
Major factors that influence pitting corrosion\(^5\)
(the pitting potential \(E_{\text{pit}}\) is generally used as the criterion for pitting)

2. Chloride concentration
The pitting resistance decreases as the Cl\(^-\) concentration increases (the log of the Cl\(^-\) concentration)

\[ E_{\text{pit}} = A \log [\text{Cl}^-] + B \]
Major factors that influence pitting corrosion\(^1\)
(the pitting potential \(E_{\text{pit}}\) is generally used as the criterion for pitting)

3. Stainless steel analysis
The pitting resistance increases strongly with some alloying elements: N, Mo, Cr

The role of the alloying elements is described by the PREN (Pitting Resistance Equivalent Number)
By calculating the PREN it is possible to compare stainless steel grades resistance against pitting. The higher the number the better the resistance.

Obviously the PREN alone cannot be used to predict whether a particular grade will be suitable for a given application.

Pitting Resistance Equivalent Number (PREN)²

\[
\text{PREN} = \text{Cr} + 3.3\text{Mo} + 16\text{N}, \quad \text{where}
\]

Cr = Chromium content
Mo = Molybdenum content
N = Nitrogen content

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<th>EN</th>
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<th>PREN</th>
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<td>-</td>
<td>10.5 - 12.5</td>
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<td>430</td>
<td>16.0 - 18.0</td>
</tr>
<tr>
<td>1.4301</td>
<td>304</td>
<td>17.5 - 20.8</td>
</tr>
<tr>
<td>1.4311</td>
<td>304LN</td>
<td>19.4 – 23.0</td>
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<tr>
<td>1.4401/4</td>
<td>316/L</td>
<td>23.1 – 28.5</td>
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<td>1.4406</td>
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<td>25.0 – 30.3</td>
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<td>1.4439</td>
<td>317L</td>
<td>31.6 – 38.5</td>
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<td>-</td>
<td>32.2 – 39.9</td>
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<tr>
<td>1.4362</td>
<td>-</td>
<td>23.1 – 29.2</td>
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<td>1.4462</td>
<td>-</td>
<td>30.8 – 38.1</td>
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<tr>
<td>1.4410</td>
<td>-</td>
<td>40</td>
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<tr>
<td>1.4501</td>
<td>-</td>
<td>40</td>
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</tbody>
</table>

Please note that the PREN does not involve Ni. The resistance to pitting corrosion does not depend upon the Ni content of the stainless steel. See next slide.
PREN of some common grades\textsuperscript{9}

Ferritic stainless steels can match 304 and 316 austenitic stainless steels in pitting corrosion resistance.

Note: Please see Appendix for EN standards designations
c) What is Crevice Corrosion$^1$?

Crevice corrosion refers to corrosion occurring in confined spaces to which the access of the working fluid from the environment is limited. These spaces are generally called crevices. Examples of crevices are gaps and contact areas between parts, under gaskets or seals, inside cracks and seams, spaces filled with deposits and under sludge piles.
Mechanism of Crevice Corrosion

- Initially, no difference between the cavity and the whole surface
- Then things change when the cavity becomes depleted in oxygen
- A set of electrochemical reactions occurs in the crevice, with the result of increasing Cl-concentration and decreasing the local pH, to the extent that passivation cannot occur
- Then the metal in the crevice undergoes uniform corrosion
Critical Pitting Resistance Temperature (CPT) and Critical Crevice Corrosion Temperature (CCT) of various austenitic & duplex grades.

Note: The higher the Temperature, the better the corrosion resistance.

Figure 9: Critical pitting and crevice corrosion temperatures for unwelded austenitic stainless steels (left side) and duplex stainless steels (right side) in the solution annealed condition (evaluated in 6% ferric chloride by ASTM G 48).

Note: Please see Appendix for EN standards designations.
How to avoid crevice corrosion

1. Optimize design:
   a) Use welded parts.
   b) Design vessels for complete drainage.

2. Clean to remove deposits (whenever possible)

3. Select a suitably corrosion resistant stainless steel (see part 4 of this chapter)
d) What is Galvanic Corrosion\textsuperscript{1}?
(Also known as bimetallic corrosion)

Corrosion that can occur when 2 metals with very different galvanic potentials are in contact.
The most anodic metal is attacked.

Example on the picture on the left: The stainless steel plate was secured to a stainless steel vessel, using mild steel bolts – resulting in galvanic corrosion of the bolts in presence of humidity, (=electrolyte)

See Reference 11
Mechanism of galvanic corrosion

- Each metal has a characteristic potential when immersed in an electrolyte (measured against a reference electrode).
- When 2 metals are connected with a conducting liquid (humidity is enough):
- And when the 2 metals have very different potentials
- A current will flow from the most electronegative (anode) to the most electropositive (cathode).
- If the anode area is small it will show dissolution of the metal
Galvanic series for metals in flowing sea water.
Basic rules on how to avoid galvanic corrosion

- Avoid situations of dissimilar metals
- When dissimilar metals are in contact make sure that the less noble metal (anode) has a much larger surface area than the more noble metal (cathode)

Examples:
  - Use Stainless steel fasteners for Aluminum products (and never Aluminum fasteners for stainless)
  - Same between stainless steel and carbon steel

In concrete (high pH) contaminated with chlorides, stainless steel rebar DOES NOT INCREASE SIGNIFICANTLY the corrosion rates of carbon steel rebar by galvanic coupling

References are given in [www.stainlesssteelrebar.org](http://www.stainlesssteelrebar.org)
e) What is Intergranular Corrosion\textsuperscript{1}?

Intergranular attack is caused by the formation of chromium carbides (Fe,Cr)\textsubscript{23}C\textsubscript{6} at grain boundaries, reducing the chromium content and the stability of the passive layer.

In the above micrographs, stainless steels specimens were polished then etched with a strong acid medium. The network of black lines corresponds to a strong chemical attack of the grain boundaries which exhibit a much lower corrosion resistance than the grains themselves.
Schematic view of Cr depletion at grain boundaries
When does Intergranular Corrosion occur?

- Properly processed stainless steels are not prone to IC
- May occur in the Heat Affected Zone of a weld (either side of a weld bead) when
  - The Carbon content is high
  - and the steel is not stabilized (by Ti, Nb, Zr * which “trap” the carbon in the matrix, making it unavailable for grain boundary carbides)

* This is why there are grades containing Ti and/or Nb and/or Zr, grades qualified as “stabilized”

To find out more about welding and other joining methods, please go to Module 09
How to avoid Intergranular Corrosion

- Use low carbon grades, below 0,03% for austenitics
- Or use stabilized grades for ferritics and austenitics
- Or on austenitics, carry out a solution annealing treatment (at 1050°C all the carbides are dissolved) followed by quenching. (This is usually impractical, however).
f) What is Stress Corrosion Cracking\(^1\) (SCC)?

- Sudden cracking and failure of a component without deformation.
- This may occur when
  - The part is stressed (by an applied load or by a residual stress)
  - The environment is aggressive (high chloride level, temperature above 50°C)
  - The stainless steel is not sufficiently SCC resistant

Ferritic and duplex (i.e. austenitic-ferritic) stainless steels are immune to SCC
Mechanism of Stress corrosion cracking (SCC)

The combined action of environmental conditions (chlorides/elevated temperature) and stress - either applied, residual or both develop the following sequence of events:

1. Pitting occurs
2. Cracks start from a pit initiation site
3. Cracks then propagate through the metal in a transgranular or intergranular mode.
4. Failure occurs

Note: Please see Appendix for EN standards designations
Avoiding SCC – two choices

Chloride induced stress corrosion cracking in standard austenitic stainless steels, viz. 1.4301/304 or 1.4401/316

Select duplex grades, more price stable (less nickel)

1.4462
1.4410
1.4501

Select austenitic stainless steels with higher content of Ni and Mo (higher corrosion resistance)

+Ni
+Mo

1.4539
1.4547 (6Mo)

Ferritic and duplex stainless steels are immune to stress corrosion cracking (because the ferrite phase, unlike the austenite phase is not sensitive to this type of corrosion).

For more information on these grades, please go to Module 04
4. How to select the right stainless steel for adequate corrosion resistance

Two different situations:
1. Structural applications (10a)
2. Other applications (10b)
4 - 1 Structural Applications

Eurocode 1-4 provides a procedure for selecting an appropriate grade of stainless steel for the service environment of structural members. (Please note that at the present time – i.e. nov 2014 – the recommendations of the Evolution Group for EN 1993-1-4 have not been yet enforced)

This procedure is presented in the next slides

It is applicable to:

- Load bearing members
- Outdoor use
- Environments without frequent immersion in sea water
- pH between 4 and 10
- No exposure to chemical process flow stream
How the procedure works

1. The environment is assessed by a Corrosion Resistance Factor (CRF) made of 3 components (CRF= F1+F2+F3) where
   a) F1 rates the risk of exposure to chlorides from salt water or deicing salts
   b) F2 rates the risk of exposure to sulphur dioxide
   c) F3 rates the cleaning regime or exposure to washing by rain
2. A matching table indicates for a given CRF the corresponding CRC class
3. The stainless steel grades are placed in corrosion resistance classes (CRC) I to V according to the CRF value

The tables are shown in the next 4 slides
**F\textsubscript{1} Risk of exposure to Cl (salt water or deicing salts)**

Note: M is distance from the sea and S is distance from roads with deicing salts

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<thead>
<tr>
<th>Number</th>
<th>Exposure Category</th>
<th>Description</th>
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<tbody>
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<td>1</td>
<td>Internally controlled environment</td>
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</tr>
<tr>
<td>0</td>
<td>Low risk of exposure</td>
<td>M &gt; 10 km or S &gt; 0.1 km</td>
</tr>
<tr>
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<td>Medium risk of exposure</td>
<td>1 km &lt; M ≤ 10 km or 0.01 km &lt; S ≤ 0.1 km</td>
</tr>
<tr>
<td>-7</td>
<td>High risk of exposure</td>
<td>0.25 km &lt; M ≤ 1 km or S ≤ 0.01 km</td>
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<tr>
<td>-10</td>
<td>Very high risk of exposure</td>
<td>Road tunnels where deicing salt is used or where vehicles might carry deicing salts into the tunnel</td>
</tr>
<tr>
<td>-10</td>
<td>Very high risk of exposure</td>
<td>North Sea coast of Germany</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All Baltic coastal areas</td>
</tr>
<tr>
<td>-15</td>
<td>Very high risk of exposure</td>
<td>Atlantic coast line of Portugal, Spain, France</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coastline of UK, France, Belgium, Netherlands, Southern Sweden</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All other coastal areas of UK, Norway, Denmark and Ireland</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mediterranean Coast</td>
</tr>
</tbody>
</table>
**F₂ Risk of exposure to sulphur dioxide**

Note: for European coastal environments the sulphur dioxide value is usually low. For inland environments the sulphur dioxide value is either low or medium. The high classification is unusual and associated with particularly heavy industrial locations or specific environments such as road tunnels. Sulphur dioxide deposition may be evaluated according to the method in ISO 9225.

<table>
<thead>
<tr>
<th>Value</th>
<th>Risk of exposure</th>
<th>Average deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Low risk of exposure</td>
<td>(&lt;10 µg/m³ average deposition)</td>
</tr>
<tr>
<td>-5</td>
<td>Medium risk of exposure</td>
<td>(10 – 90 µg/m³ average deposition)</td>
</tr>
<tr>
<td>-10</td>
<td>High risk of exposure</td>
<td>(90 – 250 µg/m³ average deposition)</td>
</tr>
</tbody>
</table>

**F₃ Cleaning regime or exposure to washing by rain**

(if $F_1 + F_2 = 0$, then $F_3 = 0$)

<table>
<thead>
<tr>
<th>Value</th>
<th>Cleanliness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Fully exposed to washing by rain</td>
</tr>
<tr>
<td>-2</td>
<td>Specified cleaning regime</td>
</tr>
<tr>
<td>-7</td>
<td>No washing by rain or No specified cleaning</td>
</tr>
</tbody>
</table>
## Matching Table

**Table A.2: Determination of Corrosion Resistance Class CRC**

<table>
<thead>
<tr>
<th>Corrosion Resistance Factor (CRF)</th>
<th>Corrosion Resistance Class (CRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRF = 1</td>
<td>I</td>
</tr>
<tr>
<td>$0 \geq CRF &gt; -7$</td>
<td>II</td>
</tr>
<tr>
<td>$-7 \geq CRF &gt; -15$</td>
<td>III</td>
</tr>
<tr>
<td>$-15 \geq CRF \geq -20$</td>
<td>IV</td>
</tr>
<tr>
<td>CRF $&lt; -20$</td>
<td>V</td>
</tr>
</tbody>
</table>
## Corrosion resistance classes of stainless steels

Table A.3: Grades in each Corrosion Resistance Class CRC

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4003</td>
<td>1.4301</td>
<td>1.4401</td>
<td></td>
<td>1.4439</td>
<td>1.4565</td>
</tr>
<tr>
<td>1.4016</td>
<td>1.4307</td>
<td>1.4404</td>
<td></td>
<td>1.4539</td>
<td>1.4529</td>
</tr>
<tr>
<td>1.4512</td>
<td>1.4311</td>
<td>1.4435</td>
<td></td>
<td>1.4462</td>
<td>1.4547</td>
</tr>
<tr>
<td></td>
<td>1.4541</td>
<td>1.4571</td>
<td></td>
<td></td>
<td>1.4410</td>
</tr>
<tr>
<td>1.4318</td>
<td>1.4429</td>
<td></td>
<td></td>
<td>1.4501</td>
<td></td>
</tr>
<tr>
<td>1.4306</td>
<td>1.4432</td>
<td></td>
<td></td>
<td>1.4507</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.4567</td>
<td>1.4578</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.4482</td>
<td>1.4662</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4362</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4062</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.4162</td>
</tr>
</tbody>
</table>

Ferritics

Std Austenitics

Mo Austenitics

Lean duplex

Super Austenitics

Duplex/super duplex

Notes: Please see the appendix for EN standards designations

This does not apply to swimming pools
4 -2 Other applications

- No specific regulations are applicable
- Grade selection must be adequate for the expected performance
- Three ways to do this:
  - Ask an expert
  - Get help from stainless steel development associations
  - Find out successful cases with similar environments (usually available)
Grade Selection Guide for Architecture

Caution: NOT applicable when

- Appearance does not matter
- Structural integrity is the primary concern
  (Then go to 4 – 1)
How the procedure works

- An evaluation score must be computed
- For each score a list of recommended stainless steel grades is provided

Criteria used in the evaluation score (see the next slides):

1. Environmental Pollution
2. Coastal exposure or Deicing salts exposure
3. Local weather pattern
4. Design considerations
5. Maintenance schedule
i. Environmental pollution

<table>
<thead>
<tr>
<th>Points</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Very low or no pollution</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Points</th>
<th>Urban pollution (Light industry, automotive exhaust)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>High *</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Points</th>
<th>Industrial pollution (Aggressive gases, iron oxides, chemicals, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Low or moderate</td>
</tr>
<tr>
<td>4</td>
<td>High *</td>
</tr>
</tbody>
</table>

* Potentially a highly corrosive location. Have a stainless steel expert evaluate the site.
## ii. A) Coastal exposure

<table>
<thead>
<tr>
<th>Points</th>
<th>Coastal or Marine Salt Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low (&gt;1.6 to 16 km (1 to 10 miles) from salt water) **</td>
</tr>
<tr>
<td>3</td>
<td>Moderate (30m to 1.6 km (100 ft to 1 mile) from salt water)</td>
</tr>
<tr>
<td>4</td>
<td>High (&lt;30m (100 ft) from salt water)</td>
</tr>
<tr>
<td>5</td>
<td>Marine (some salt spray or occasional splashing) *</td>
</tr>
<tr>
<td>8</td>
<td>Severe Marine (continuous splashing) *</td>
</tr>
<tr>
<td>10</td>
<td>Severe Marine (continuous immersion) *</td>
</tr>
</tbody>
</table>

* Potentially a highly corrosive location. Have a stainless steel corrosion expert evaluate the site.

** This range shows how far chlorides are typically found from large salt water bodies. Some locations of this type are exposed to chlorides but others are not.
### ii. B) Deicing salts exposure

<table>
<thead>
<tr>
<th>Points</th>
<th>Deicing Salt Exposure (Distance from road or ground)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No salt was detected on a sample from the site and no change in exposure conditions is expected.</td>
</tr>
<tr>
<td>0</td>
<td>Traffic and wind levels on nearby roads are too low to carry chlorides to the site and no deicing salt is used on sidewalks</td>
</tr>
<tr>
<td>1</td>
<td>Very low salt exposure (≥10 m to 1 km (33 to 3,280 ft) or 3 to 60 floors) **</td>
</tr>
<tr>
<td>2</td>
<td>Low salt exposure (&lt; 10 to 500 m (33 to 1600 ft) or 2 to 34 floors) **</td>
</tr>
<tr>
<td>3</td>
<td>Moderate salt exposure (&lt; 3 to 100 m (10 to 328 ft) or 1 to 22 floors) **</td>
</tr>
<tr>
<td>4</td>
<td>High salt exposure (&lt;2 to 50 m (6.5 to 164 ft) or 1 to 3 floors) * **</td>
</tr>
</tbody>
</table>

* Potentially a highly corrosive location. Have a stainless steel corrosion expert evaluate the site.
** This range shows how far this chloride concentration has been found from small rural and large high traffic roads. Test surface chloride concentrations.

Note: if both coastal exposure and deicing salts are present, please ask an expert
### iii. Local weather pattern

<table>
<thead>
<tr>
<th>Points</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>Temperature or cold climates, regular heavy rain</td>
</tr>
<tr>
<td>-1</td>
<td>Hot or cold climates with typical humidity below 50%</td>
</tr>
<tr>
<td>0</td>
<td>Temperature or cold climate, occasional heavy rain</td>
</tr>
<tr>
<td>0</td>
<td>Tropical or subtropical, wet, regular or seasonal very heavy rain</td>
</tr>
<tr>
<td>1</td>
<td>Temperature climate, infrequent rain, humidity above 50%</td>
</tr>
<tr>
<td>1</td>
<td>Regular very light rain or frequent fog</td>
</tr>
<tr>
<td>2</td>
<td>Hot, humidity above 50%, very low or no rainfall ***</td>
</tr>
</tbody>
</table>

*** If there is also salt or pollution exposure, have a stainless steel corrosion expert evaluate the site.
### iv. Design Considerations

<table>
<thead>
<tr>
<th>Points</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Boldly exposed for easy rain cleaning</td>
</tr>
<tr>
<td>0</td>
<td>Vertical surfaces with a vertical or no finish grain</td>
</tr>
<tr>
<td>-2</td>
<td>Surface finish is pickled, electropolished, or roughness ≤ Ra 0.3 μm (12 μin)</td>
</tr>
<tr>
<td>-1</td>
<td>Surface finish roughness Ra 0.3 μm (12 μin) &lt; X ≤ Ra 0.5 μm (20 μin)</td>
</tr>
<tr>
<td>1</td>
<td>Surface finish roughness Ra 0.5 μm (20 μin) &lt; X ≤ Ra 1 μm (40 μin)</td>
</tr>
<tr>
<td>2</td>
<td>Surface finish roughness &gt; Ra 1 μm (40 μin)</td>
</tr>
<tr>
<td>1</td>
<td>Sheltered location or unsealed crevices ***</td>
</tr>
<tr>
<td>1</td>
<td>Horizontal surfaces</td>
</tr>
<tr>
<td>1</td>
<td>Horizontal finish grain orientation</td>
</tr>
</tbody>
</table>

*** If there is also salt or pollution exposure, have a stainless steel corrosion expert evaluate the site.

---


---

This table shows that corrosion resistance depends also on surface finish. For more information on the available finishes, please go to Module 08.
v. Maintenance schedule

<table>
<thead>
<tr>
<th>Points</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not washed</td>
</tr>
<tr>
<td>-1</td>
<td>Washed at least naturally</td>
</tr>
<tr>
<td>-2</td>
<td>Washed four or more times per year</td>
</tr>
<tr>
<td>-3</td>
<td>Washed at least monthly</td>
</tr>
</tbody>
</table>
Stainless Steel selection scoring system

<table>
<thead>
<tr>
<th>Total score</th>
<th>Stainless Steel Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 2</td>
<td>Type 304/304L is generally the most economical choice</td>
</tr>
<tr>
<td>3</td>
<td>Type 316/316L or 444 is generally the most economical choice</td>
</tr>
<tr>
<td>4</td>
<td>Type 317L or a more corrosion resistant stainless steel is suggested</td>
</tr>
<tr>
<td>≥ 5</td>
<td>A more corrosion resistant stainless steel such as 4462, 317LMN, 904L, super duplex, super ferritic or a 6% molybdenum super austenitic stainless steel may be needed</td>
</tr>
</tbody>
</table>

Note: please see the appendix for EN standard designations

Proper selection of the stainless steel grades will lead to a long, maintenance-free, service life with a low life cycle cost and an excellent sustainability.

For more information sustainability, please go to Module 11
Conclusion

- Proper selection of the right stainless steel grade for the application and the environment deserves attention.
- When this is done, stainless steel will provide unlimited service life without maintenance.

You will find in Module 2 a wide range of successful applications of stainless steels, and in Module 1 timeless art, worldwide!
5. References

1. An excellent course on corrosion. Please look at chapters 7 (Galvanic Corrosion), 8 (intergranular corrosion), 11 (crevice corrosion) 12 (pitting) 14 (Stress corrosion cracking) and 15 (stress corrosion cracking of stainless steels) Original source: http://corrosion.kaist.ac.kr Dowloads available from: https://www.worldstainless.org/Files/issf/Education_references/Zrefs_on_corrosion.zip

2. Some basics on corrosion from NACE http://corrosion-doctors.org/Corrosion-History/Course.htm#Scope

3. An online course on corrosion http://www.corrosionclinic.com/corrosion_online_lectures/ME303L10.HTM#top

4. Information on electrochemical testing http://mee-inc.com/esca.html

5. Ugitech: private communication

6. BSSA (British Stainless Steel Association) website “Calculation of pitting resistance equivalent numbers (PREN)” http://www.bssa.org.uk/topics.php?article=111


## Appendix: Designations

<table>
<thead>
<tr>
<th>EN Designation</th>
<th>Steel number</th>
<th>AISI</th>
<th>UNS</th>
<th>Other US</th>
<th>Generic/Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>X2CrNi12</td>
<td>1.4003</td>
<td>$40977</td>
<td>3CR12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrTi12</td>
<td>1.4512</td>
<td>409</td>
<td>$40900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6CrNiTi12</td>
<td>1.4516</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6Cr13</td>
<td>1.4000</td>
<td>410S</td>
<td>$41008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6CrAl13</td>
<td>1.4002</td>
<td>405</td>
<td>$40500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6Cr17</td>
<td>1.4016</td>
<td>430</td>
<td>$43000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X3CrTi17</td>
<td>1.4510</td>
<td>439</td>
<td>$43035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X3CrNb17</td>
<td>1.4511</td>
<td>430N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6CrMo17-1</td>
<td>1.4113</td>
<td>434</td>
<td>$43400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrMoTi18-2</td>
<td>1.4521</td>
<td>444</td>
<td>$44400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Ferritic stainless steels - standard grades**

<table>
<thead>
<tr>
<th>EN Designation</th>
<th>Steel number</th>
<th>AISI</th>
<th>UNS</th>
<th>Other US</th>
<th>Generic/Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>X10CrNi18-8</td>
<td>1.4310</td>
<td>301</td>
<td>S30100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNi18-9</td>
<td>1.4307</td>
<td>304L</td>
<td>S30403</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNi19-11</td>
<td>1.4306</td>
<td>304L</td>
<td>S30403</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNiN18-10</td>
<td>1.4311</td>
<td>304LN</td>
<td>S30453</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X5CrNi18-10</td>
<td>1.4301</td>
<td>304</td>
<td>S30400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6CrNiTi18-10</td>
<td>1.4541</td>
<td>321</td>
<td>S32100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X4CrNi18-12</td>
<td>1.4303</td>
<td>305</td>
<td>S30500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNiMo17-12-2</td>
<td>1.4404</td>
<td>316L</td>
<td>S31603</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNiMo17-12-2</td>
<td>1.4401</td>
<td>316</td>
<td>S31600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6CrNiMo17-12-2</td>
<td>1.4571</td>
<td>316Ti</td>
<td>S31635</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNiMo17-12-3</td>
<td>1.4432</td>
<td>316L</td>
<td>S31603</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNiMo17-14-3</td>
<td>1.4435</td>
<td>316L</td>
<td>S31603</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2CrNiMoN17-13-5</td>
<td>1.4439</td>
<td>317L</td>
<td>S31603</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X1NiCrMoCu25-20-5</td>
<td>1.4539</td>
<td>N08904</td>
<td>904L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Martensitic stainless steels - standard grades**

<table>
<thead>
<tr>
<th>EN Designation</th>
<th>Steel number</th>
<th>AISI</th>
<th>UNS</th>
<th>Other US</th>
<th>Generic/Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>X12Cr13</td>
<td>1.4006</td>
<td>410</td>
<td>$41000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X20Cr13</td>
<td>1.4021</td>
<td>420</td>
<td>$42000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X30Cr13</td>
<td>1.4028</td>
<td>420</td>
<td>$42000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X3CrNiMo13-4</td>
<td>1.4313</td>
<td>41500</td>
<td>F6NM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X4CrNiMo16-5-1</td>
<td>1.4418</td>
<td>248</td>
<td>SV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Martensitic and precipitation-hardening steels - special grades**

<table>
<thead>
<tr>
<th>EN Designation</th>
<th>Steel number</th>
<th>AISI</th>
<th>UNS</th>
<th>Other US</th>
<th>Generic/Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>X5CrNiCuNb16-4</td>
<td>1.4542</td>
<td>$17400</td>
<td>17-4 PH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: This is a simplified table. For special grades, please look at reference 17.
Thank you

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 06
Mechanical Properties
Please note:

This chapter is about non-structural applications (for structural applications please go to chapter 7)
Non-structural applications usually do not demand high strength. Material selection optimizes a set of properties.
Mechanical properties:

1. Yield Strength (MPa)
2. Ultimate Tensile Strength (MPa)
3. Elongation (%)
4. Young’s Modulus (MPa)
5. Impact resistance
6. Fire Resistance
7. Creep resistance
8. Fatigue resistance
9. Properties at cryogenic temperatures
10. Properties at elevated temperatures

Properties 1-6 are the most relevant to architecture & engineering
The mechanical properties of stainless steels are well known and minimum values guaranteed international standards.

- **Main standards**
  - ISO
  - ASTM/AISI
  - EN
  - JS
  - Others

- **Applicable to all grades & products:**
  - Sheets
  - Plates
  - Bars
  - Tubes
  - Forgings
  - Castings
  - Fasteners
  - Wires
  - Welding products
  - ...etc
Mechanical Properties: background information

Tensile and impact tests:
Please have a look at the videos!

http://www.youtube.com/watch?v=67fSwljYJ-E

http://www.youtube.com/watch?v=_b6Ul5ANNl0

http://www.youtube.com/watch?v=t9eB0PKYAt8

http://www.youtube.com/watch?v=tpGhqQvftAo

For more details on Mechanical Properties and on the derivation of stress strain curves go to:

http://www.engineeringarchives.com/les_mom_truestresstruestrainengstressengstrain.html

http://www.engineeringarchives.com/les_mom_stressstrain-diagram.html

& previous & following pages on the website & refs 1-2
Typical tensile curves of stainless steels

Typical stress-strain curves of different types of stainless steels

A wide range of properties is available

From

- High strength and low elongation to
- Lower strength and very high elongation
Comparison between carbon steels and stainless steels

Stainless steels do not match carbon steel strength level.
Mechanical Properties of stainless steels\textsuperscript{3-7}

M: Martensitics\textsuperscript{*}
M1 C-Cr-Ni grades
M2 C-Cr grades
D: Duplex\textsuperscript{**}
F: Ferritics\textsuperscript{**}
A1: Austenitics, annealed\textsuperscript{**}
A2: Austenitics, cold-worked\textsuperscript{***}

\textsuperscript{*} EN 10088-3, (heat treated)
\textsuperscript{**} EN 10088-2 (annealed)
\textsuperscript{***} EN 10088-2 (Cold Worked)
Higher tensile strength by cold work$^7$

High strength cold-worked stainless grades offer a big potential for future developments.

For structural applications, please go chapter 7
A lot of experimental data is available in reference 8 below.
Charpy Impact toughness of stainless steels (ref 8)

Note: These curves are for thick products (bars or plates)
Thin products exhibit a larger fracture toughness.
Hence ferritic grades can be used for construction purposes in sheet form but not in plates or bars
Fracture mechanics
Effect of thickness on fracture toughness
(see also ref 9, Figure 5)
Austenitic Stainless Steels offer a much better strength retention factor than Carbon Steel above 500°C
Fire resistance\textsuperscript{9-10}

Stainless Steels offer a much better stiffness retention factor than Carbon Steel above 300°C.
Comparison of Tensile properties of various alloys

Stainless steels show higher tensile properties than Mild steel, Aluminium and Brass. Duplex grades offer an excellent strength/ductility ratio.
References and sources

8. Source of the graph: Ugitech (http://www.ugitech.com/)
Thank you

Test your knowledge of stainless steel here:
https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Part A: Structural Applications of Stainless Steel Reinforcing Bar

See also: stainlesssteelfrebar.org
Wrong choice of materials can lead to big problems
A textbook case: Corrosion of the Turcot highway interchange in Montreal \(^1,^2\)

- A key interchange between Decarie (North-South) and Ville Marie (East-West) highways, built in 1966.
- Over 300,000 vehicles per day
- Made of reinforced concrete, badly corroded today by deicing salts
It had to be replaced

- In spite of constant supervision and repairs, it had to be replaced,
  - Cost CAD 3000M.
  - Moreover, CAD 254M had to be spent to ensure safety until its replacement in 2018

- Lifespan of the structure was only 50 years!
How reinforced concrete can be damaged by corrosion
Diffusion of corrosive ions (usually chlorides) into concrete:

Steps:

1. Once corrosive ions reach the carbon steel rebar (t0), corrosion begins
2. Corrosion products, which occupy a greater volume than steel, exert an outwards pressure
3. Concrete cracking occurs (t1), opening easy access to chlorides
4. Concrete cover cracks (spalling) (t3), exposing the rebar
5. If unattended, corrosion continues until the rebar cannot bear the applied tensile stresses and the structure collapses (t4)
Corrosion of rebar in concrete

- In the high pH of concrete, in the absence of chlorides, carbon steel rebar is in a passive state (i.e. does not corrode)
- A low chloride content is sufficient to activate corrosion of carbon steel
- Stainless steel properly specified never corrodes.
- Galvanic coupling between stainless steel rebar (anode) and carbon steel rebar (cathode) contributes only to ~1% of the overall corrosion rate*. It is therefore negligible.
- Type of concrete, temperature, exposure conditions, distance between carbon steel rebar and surface, etc... have a strong influence on the corrosion rate of the carbon steel rebar

* Specific references are provided at the end of the presentation
Concrete often exhibits cracks, though which corrosive ions reach quickly the steel. Here are some causes of crack formation. Please note that cracks do not take place immediately, and will also occur in concealed areas, where they cannot be repaired.

<table>
<thead>
<tr>
<th>Type of cracking</th>
<th>Form of crack</th>
<th>Primary Cause</th>
<th>Time of Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic settlement</td>
<td>Above and aligned with steel reinforcement</td>
<td>Subsidence around rebar; excessive water in the mix</td>
<td>10 minutes to three hours</td>
</tr>
<tr>
<td>Plastic shrinkage</td>
<td>Diagonal or random</td>
<td>Excessive early evaporation</td>
<td>30 minutes to six hours</td>
</tr>
<tr>
<td>Thermal expansion and contraction</td>
<td>Transverse (example: across the pavement)</td>
<td>Excessive heat generation or temperature gradients</td>
<td>One day to two or three weeks</td>
</tr>
<tr>
<td>Drying shrinkage</td>
<td>Transverse or pattern</td>
<td>Excessive water in the mix; poor joint placement; joints over-spaced</td>
<td>Weeks to months</td>
</tr>
<tr>
<td>Freezing and thawing</td>
<td>Parallel to the concrete surface</td>
<td>Inadequate air entrainment; non-durable coarse aggregate</td>
<td>After one or more winters</td>
</tr>
<tr>
<td>Corrosion of reinforcement</td>
<td>Above reinforcement</td>
<td>Inadequate concrete cover; ingress of moisture or chloride</td>
<td>More than two years</td>
</tr>
<tr>
<td>Alkali-aggregate reaction</td>
<td>Pattern cracks; cracks parallel to joints or edges</td>
<td>Reactive aggregate plus moisture</td>
<td>Typically, over five years, but may be much sooner with highly reactive aggregate</td>
</tr>
<tr>
<td>Sulfate attack</td>
<td>Pattern cracks</td>
<td>External or internal sulfates promoting the formation of ettringite</td>
<td>One to five years</td>
</tr>
</tbody>
</table>
Major civil engineering structures must last over 100 years now
Haynes Inlet Slough Bridge, Oregon, USA 2004

An unusual arch-hinged bridge with 400 tons of stainless steel reinforcing bar in its deck. The 230m-long link over Haynes Inlet Slough is expected to last 120 maintenance-free years. Although stainless steel costs a lot more than average steel, the bridge life-cycle cost will be greatly reduced.
Broadmeadow Bridge, Dublin, Ireland (2003)

A new construction built over the estuary using 105MT of stainless steel reinforcement in the columns and parapets.
Dam repair Bayonne, France

Dam built in the 1960s to protect the entrance to the harbour

The ocean side is higher and protected by 40T blocks which must be replaced as the storms wear them

On the river side a 7m wide platform allows the heavy-duty cranes to lift the blocks

Cracks on the deck and wall required repairs
Section through the sea wall

Sea wall repair
Bayonne, France

Platform and sea wall have been reinforced with lean duplex stainless steel (EN 1.4362)\textsuperscript{11}

Sea wall repair under way

Early 2014 gale over the dam
To assure long-term (100 years) durability and resistance to the corrosive attack of the area’s marine environment and road salt, the bridge units and parapet barriers were reinforced with stainless steel grade 2205 rebar.
When should stainless steel rebar be considered?

- In corrosive environments:
  - Sea water and even more in hot climates
    - Bridges
    - Piers
    - Docks
    - Anchors for lamp posts, railings, ...
    - Sea walls
    - ..... 
  - Deicing salts
    - Bridges
    - Traffic overpasses and interchanges
    - Parking garages
- Waste water treatment tanks
- Desalination plants
- In structures with a very long life
  - Repairs of historic structures
  - Nuclear waste storage
- In unknown environments in which
  - Inspection is impossible,
  - Repairs are almost impossible or very expensive
<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epoxy coating</strong></td>
<td>Lower initial costs</td>
<td>▪ cannot be bent without cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Requires careful handling to avoid damaging it during installation</td>
</tr>
<tr>
<td><strong>Galvanizing</strong></td>
<td>Lower initial costs</td>
<td>▪ cannot be bent without cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ No longer effective when the zinc coating has been corroded</td>
</tr>
<tr>
<td><strong>Fiber-reinforced Polymers</strong></td>
<td>Lower initial costs</td>
<td>▪ Cannot be bent without cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ No heat resistance and poor impact resistance in harsh winters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Lower stiffness than that of steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Cannot be recycled</td>
</tr>
<tr>
<td><strong>STAINLESS STEEL</strong></td>
<td>Low Life Cycle cost:</td>
<td>▪ Higher initial cost, but no more than a few % when</td>
</tr>
<tr>
<td></td>
<td>• Design similar to C-steels</td>
<td>✓ Stainless is selected for the critical areas</td>
</tr>
<tr>
<td></td>
<td>• Mixed C-steel/stainless reinforcements</td>
<td>✓ Lean duplex grades are selected</td>
</tr>
<tr>
<td></td>
<td>work well</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Easy installation, insensitive to poor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>workmanship</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No maintenance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No life limit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Allows a thinner concrete cover</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Better fire resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 100% Recycled to premium stainless</td>
<td></td>
</tr>
</tbody>
</table>
## Comparison of stainless rebar with alternative solutions

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
</table>
| Cathodic protection    | Lower initial costs?  
                          | Often used for repairs   | ▪ Requires careful design for overall protection  
                          | ▪ Requires careful installation to maintain proper electrical contacts   
                          | ▪ Requires a permanent source of current (which must be monitored and maintained) or sacrificial anodes that require monitoring & replacement |
| Membranes/sealants     | Lower initial costs?                 | ▪ Require careful installation (bubbles)  
                          | ▪ Cannot be installed in any weather  
                          | ▪ Performance over time debatable   
                          | ▪ Limited to horizontal surfaces |
References

7. https://www.roadsbridges.com/willing-bend-0 (Oregon)
8. http://structurae.net/structures/data/index.cfm?id=s0011506 (Oregon)
11. Courtesy Ugitech SA
19. http://www.sintef.no/upload/Byggforsk/Publikasjoner/Prrapp%20405.pdf (general)
References on Galvanic Coupling


7. S. Qian, D. Qu & G. Coates Galvanic Coupling Between Carbon Steel and Stainless Steel Reinforcements Canadian Metallurgical Quarterly Volume 45, 2006 - Issue 4 Pages 475-483 Published online: 18 Jul 2013


Thank you

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Part B

Structural Applications of Stainless Steel Plates, Sheets, Bars, ....
Structural Stainless Steel
Designing with stainless steel

Barbara Rossi, Maarten Fortan
Civil Engineering department,
KU Leuven, Belgium

Based on a previous version prepared by Nancy Baddoo
Steel Construction Institute, Ascot, UK
Outline

- Examples of structural applications
- Material mechanical characteristics
- Design according to Eurocode 3
- Alternative methods
- Deflections
- Additional information
- Resources for engineers
Section 1

Examples of structural applications
Station Sint Pieters, Ghent (BE)
Arch : Wefirna
Eng. Off.: THV Van Laere-Braekel Aero
Military School in Brussels
Arch: AR.TE
Eng. Off.: Tractebel Development
La Grande Arche, Paris
Arch : Johan Otto von Spreckelsen
Eng. Off.: Paul Andreu
Villa Inox (FIN)
La Lentille de Saint-Lazare, Paris, (France)
Arch: Arte Charpentiers & Associés
Eng. Off.: Mitsu Edwards
Station in Porto (Portugal)
Torno Internazionale S.P.A. Headquarters Milan, (IT), Stainless steel grade: EN 1.4404 (AISI 316L)
Architect : Dante O. BENINI & Partners Architects

Photography: Toni Nicolino / Nicola Giacomin
Stainless steel frames in nuclear power plant

Photography: Stainless Structurals LLC
Stainless steel façade supports, Tampa, (USA)

Photography: TriPyramid Structures, Inc.
Stainless steel I-shaped beams,
Thames Gateway Water Treatment Works, (UK)

Photography: Interserve
Section 2

Material mechanical characteristics
Stress-Strain characteristics: Carbon steel vs stainless steel

Stainless steel exhibits fundamentally different $\sigma$-$\varepsilon$ behaviour to carbon steel.

- **Stainless steel** exhibits gradually yielding behaviour, with high strain-hardening.
- **Carbon steel** has a sharply defined yield point with a plastic yield plateau.

\[ \text{Stress } \sigma \] \[ \text{Strain } \varepsilon \]
Stress-strain characteristics – low strain

Stress-strain response depends on the family.
Design strength of stainless steel

Minimum specified 0.2% proof strength are given in EN 10088-4 and -5

Austenitics: \( f_y = 220-350 \) MPa
Duplexes: \( f_y = 400-480 \) Mpa
Ferritics: \( f_y = 210-280 \) MPa

Young’s modulus: \( E=200,000 \) to 220,000 MPa
# Design strength of stainless steel

<table>
<thead>
<tr>
<th>Grade</th>
<th>Family</th>
<th>Yield strength (N/mm²) 0.2% proof strength</th>
<th>Ultimate strength (N/mm²)</th>
<th>Young’s Modulus (N/mm²)</th>
<th>Fracture strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4301 (304)</td>
<td>Austenitic</td>
<td>210</td>
<td>520</td>
<td>200000</td>
<td>45</td>
</tr>
<tr>
<td>1.4401 (316)</td>
<td>Austenitic</td>
<td>220</td>
<td>520</td>
<td>200000</td>
<td>40</td>
</tr>
<tr>
<td>1.4062</td>
<td>Duplex</td>
<td>450</td>
<td>650</td>
<td>200000</td>
<td></td>
</tr>
<tr>
<td>1.4462</td>
<td>Duplex</td>
<td>460</td>
<td>640</td>
<td>200000</td>
<td></td>
</tr>
<tr>
<td>1.4003</td>
<td>Ferritic</td>
<td>250</td>
<td>450</td>
<td>220000</td>
<td></td>
</tr>
</tbody>
</table>
Strain hardening (work hardening or cold working)

- Increased strength by plastic deformation
- Caused by cold-forming, either during steel production operations at the mill or during fabrication processes

During the fabrication of a rectangular hollow section, the 0.2% proof strength increases by about 50% in the cold-formed corners of cross sections!
Strain hardening
(work hardening or cold working)

• Strength enhancement during forming
Strain hardening – not always useful

- Heavier and more powerful fabrication equipment
- Greater forces are required
- Reduced ductility (however, the initial ductility is high, especially for austenitics)
- Undesirable residual stresses may be produced
Ductility and toughness

- **Ductility** - ability to be stretched without breaking

- **Toughness** - ability to absorb energy & plastically deform without fracturing

![Stress vs. Strain Graph](image)

- **Brittle**
- **Ductile**

Area under curve = absorbed energy
Stress-Strain Characteristics – high strain

- Duplex stainless steel
- Carbon steel S355
- Austenitic stainless steel
Blast/impact resistant structures

Security bollard

A trapezoidal blast resistant wall being fabricated for the topsides of an offshore platform
Stress-strain characteristics

Nonlinearity leads to

– different limiting width to thickness ratios for local buckling

– different member buckling behaviour in compression and bending

– greater deflections
Impact on buckling performance

- **Low slenderness**
columns attain/exceed the squash load

  ⇒ *benefits* of strain hardening apparent
  ss behaves at least *as well as* cs

- **High slenderness**
axial strength low, stresses low and in linear region

  ⇒ ss behaves *similarly* to cs, providing geometric and residual stresses similar
Impact on buckling performance

- Intermediate slenderness
  average stress in column lies between the limit of proportionality and the 0.2% permanent strain,
  ss column less strong than cs column
Material at elevated temperature

\[ k_{0.2p,q} = \text{strength reduction factor at 0.2\% proof strain} \]

\[ k_{2,q} = \text{strength reduction factor at 2\% total strain} \]
Material at elevated temperature

Stiffness reduction factors $k_{E,\theta}$

- **Stainless Steel**
- **Carbon steel**

Temperature (°C)

Stiffness reduction factor
Material at elevated temperature

Thermal expansion

- Carbon steel
- Stainless steel
Section 4

Design according to Eurocode 3
International design standards

What design standards are available for structural stainless steel?

Hamilton Island Yacht Club, Australia
Eurocodes are an Integrated suite of structural design codes covering all common construction materials.
Eurocode 3: Part 1 (EN 1993-1)

EN 1993-1-2 Structural fire design.
EN 1993-1-3 Cold-formed members and sheeting.
EN 1993-1-4 Stainless steels.
EN 1993-1-5 Plated structural elements.
EN 1993-1-6 Strength and stability of shell structures.
EN 1993-1-7 Strength & stability of planar plated structures transversely loaded.
EN 1993-1-8 Design of joints.
EN 1993-1-10 Selection of steel for fracture toughness and through-thickness properties.
EN 1993-1-11 Design of structures with tension components
EN 1993-1-12 Supplementary rules for high strength steels
Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

- **Design of steel structures.** Supplementary rules for stainless steels (2006)
  - Modifies and supplements rules for carbon steel given in other parts of Eurocode 3 where necessary
  - Applies to buildings, bridges, tanks etc
Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

- Follow same basic approach as carbon steel

- Use same rules as for carbon steel for tension members & restrained beams

- Some differences in section classification limits, local buckling and member buckling curves apply due to:
  - non-linear stress strain curve
  - strain hardening characteristics
  - different levels of residual stresses
Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

Types of members

- Hot rolled and welded
- Cold-formed
- Bar

Scope

- Members and connections
- Fire (by reference to EN 1993-1-2)
- Fatigue (by reference to EN 1993-1-9)

Number of grades

<table>
<thead>
<tr>
<th>Family</th>
<th>EC3-1-4</th>
<th>Future revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Austenitic</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Duplex</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>
Other design standards

- **Japan** – two standards: one for cold formed and one for welded stainless members

- **South Africa, Australia, New Zealand** - standards for cold formed stainless members

- **Chinese** - standard under development

- **US** - ASCE specification for cold-formed members and AISC Design Guide for hot rolled and welded structural stainless steel
What are the design rules for stainless steel given in EN 1993-1-4 and the main differences with carbon steel equivalents?
Section classification & local buckling expressions in EN 1993-1-4

- Lower limiting width-to-thickness ratios than for carbon steel
- Slightly different expressions for calculating effective widths of slender elements

However…

The next version of EN 1993-1-4 will contain less conservative limits & effective width expressions.
Section classification & local buckling expressions in EN 1993-1-4

- **Internal compression parts**

\[ \varepsilon = \sqrt{\frac{235}{f_y \cdot \frac{E}{210000}}} \]

<table>
<thead>
<tr>
<th>Class</th>
<th>EC3-1-1: carbon steel</th>
<th>EC3-1-4: stainless steel</th>
<th>EC3-1-4: Future revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( c/t \leq 72\varepsilon )</td>
<td>( c/t \leq 56\varepsilon )</td>
<td>( c/t \leq 72\varepsilon )</td>
</tr>
<tr>
<td></td>
<td>( c/t \leq 33\varepsilon )</td>
<td>( c/t \leq 25,7\varepsilon )</td>
<td>( c/t \leq 33\varepsilon )</td>
</tr>
<tr>
<td>2</td>
<td>( c/t \leq 83\varepsilon )</td>
<td>( c/t \leq 58,2\varepsilon )</td>
<td>( c/t \leq 76\varepsilon )</td>
</tr>
<tr>
<td></td>
<td>( c/t \leq 38\varepsilon )</td>
<td>( c/t \leq 26,7\varepsilon )</td>
<td>( c/t \leq 35\varepsilon )</td>
</tr>
<tr>
<td>3</td>
<td>( c/t \leq 124\varepsilon )</td>
<td>( c/t \leq 74,8\varepsilon )</td>
<td>( c/t \leq 90\varepsilon )</td>
</tr>
<tr>
<td></td>
<td>( c/t \leq 42\varepsilon )</td>
<td>( c/t \leq 30,7\varepsilon )</td>
<td>( c/t \leq 37\varepsilon )</td>
</tr>
</tbody>
</table>
Section classification & local buckling expressions in EN 1993-1-4

- External compression parts

\[ \varepsilon = \sqrt{\frac{235}{f_y}} \frac{E}{210000} \]

<table>
<thead>
<tr>
<th>Class</th>
<th>Compression</th>
<th>Compression Welded</th>
<th>Compression Cold-formed</th>
<th>Compression Future revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>c/t ≤ 9ε</td>
<td>c/t ≤ 9ε</td>
<td>c/t ≤ 10ε</td>
<td>c/t ≤ 9ε</td>
</tr>
<tr>
<td>2</td>
<td>c/t ≤ 10ε</td>
<td>c/t ≤ 9,4ε</td>
<td>c/t ≤ 10,4ε</td>
<td>c/t ≤ 10ε</td>
</tr>
<tr>
<td>3</td>
<td>c/t ≤ 14ε</td>
<td>c/t ≤ 11ε</td>
<td>c/t ≤ 11,9ε</td>
<td>c/t ≤ 14ε</td>
</tr>
</tbody>
</table>
Design of columns & beams

- In general use **same approach** as for carbon steel

- **But use different buckling curves** for buckling of columns and unrestrained beams (LTB)

- Ensure you **use the correct** $f_y$ for the grade (minimum specified values are given in EN 10088-4 and -5)
“Perfect” column behaviour

Two bounds: Yielding and buckling:

\[ N_{Ed} \]

\[ L_{cr} \]

- **Material yielding (squashing)**
- **Euler (critical) buckling** \( N_{cr} \)

Load

\( A_f_y \)

Yielding

Buckling

Slenderness
Column buckling

Compression buckling resistance $N_{b,Rd}$:

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}}$$

for Class 1, 2 and 3

Reduction factor

$$N_{b,Rd} = \frac{\chi A_{\text{eff}} f_y}{\gamma_{M1}}$$

for (symmetric) Class 4
Column buckling

Non-dimensional slenderness: \( \overline{\lambda} \)

\[
\overline{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}} \quad \text{for Class 1, 2 and 3 cross-sections}
\]

\[
\overline{\lambda} = \sqrt{\frac{A_{\text{eff}} f_y}{N_{cr}}} \quad \text{for Class 4 cross-sections}
\]

\( N_{cr} \) is the elastic critical buckling load for the relevant buckling mode based on the gross properties of the cross-section.
Column buckling

Reduction factor: $\chi$

$$\chi = \frac{1}{\phi + (\phi^2 - \lambda^2)^{0.5}} \leq 1$$

$$\phi = 0.5 (1 + \alpha (\lambda - \lambda_0) + \lambda^2)$$

- Imperfection factor
- Plateau length
Column buckling

- Choice of buckling curve depends on cross-section, manufacturing route and axis

<table>
<thead>
<tr>
<th>Buckling mode</th>
<th>Type of member</th>
<th>$\alpha$</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural</td>
<td>Cold formed open sections</td>
<td>0.49</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Hollow sections (welded and seamless)</td>
<td>0.49</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Welded open sections (major axis)</td>
<td>0.49</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Welded open sections (minor axis)</td>
<td>0.76</td>
<td>0.20</td>
</tr>
<tr>
<td>Torsional and torsional-flexural</td>
<td>All members</td>
<td>0.34</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Extract from EN 1993-1-4
Eurocode 3 Flexural buckling curves

- **Stainless steel**: hollow sections (welded + seamless), cold formed channels
- **Stainless steel**: welded I-sections
- **Carbon steel**: welded I-sections, cold formed hollow sections, cold formed channels
- **Carbon steel**: hot finished hollow sections
Eurocode 3 Flexural buckling example

- Cold formed rectangular hollow section submitted to concentric compression

<table>
<thead>
<tr>
<th></th>
<th>Carbon steel</th>
<th>Austenitic stainless steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>S235</td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>$f_y$ [N/mm²]</td>
<td>235</td>
<td>230</td>
</tr>
<tr>
<td>$E$ [N/mm²]</td>
<td>210000</td>
<td>200000</td>
</tr>
</tbody>
</table>
Eurocode 3 flexural buckling example

**EC 3-1-1: S235**

- Classification

\[ \varepsilon = \sqrt{\frac{235}{f_y}} = 1 \]

- All internal parts

\[ \frac{c}{t} = 21 < 33 = 33\varepsilon \]

Class 1

Cross-section = class 1

**EC 3-1-4: Austenitic**

- Classification

\[ \varepsilon = \sqrt{\frac{235}{f_y} \frac{E}{210000}} = 0.99 \]

- All internal parts

\[ \frac{c}{t} = 21 < 25.35 = 25.7\varepsilon \]

Class 1

Cross-section = class 1
## Eurocode 3 flexural buckling example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EC 3-1-1: S355</th>
<th>EC 3-1-4: Duplex</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ [$\text{mm}^2$]</td>
<td>1495</td>
<td>1495</td>
</tr>
<tr>
<td>$f_y$ [N/$\text{mm}^2$]</td>
<td>235</td>
<td>230</td>
</tr>
<tr>
<td>$\gamma_{M0}$ [-]</td>
<td>1</td>
<td>1,1</td>
</tr>
<tr>
<td>$N_{c,Rd}$ [kN]</td>
<td>351</td>
<td>313</td>
</tr>
<tr>
<td>$L_{cr}$ [mm]</td>
<td>2100</td>
<td>2100</td>
</tr>
<tr>
<td>$\lambda_1$ [-]</td>
<td>93,9</td>
<td>92,6</td>
</tr>
<tr>
<td>$\bar{\lambda}$ [-]</td>
<td>0,575</td>
<td>0,583</td>
</tr>
<tr>
<td>$\alpha$ [-]</td>
<td>0,49</td>
<td>0,49</td>
</tr>
<tr>
<td>$\bar{\lambda}_0$ [-]</td>
<td>0,2</td>
<td>0,4</td>
</tr>
<tr>
<td>$\phi$ [-]</td>
<td>0,76</td>
<td>0,71</td>
</tr>
<tr>
<td>$\chi$ [-]</td>
<td>0,80</td>
<td>0,89</td>
</tr>
<tr>
<td>$\gamma_{M1}$ [-]</td>
<td>1</td>
<td>1,1</td>
</tr>
<tr>
<td>$N_{b,Rd}$ [kN]</td>
<td>281</td>
<td>277</td>
</tr>
</tbody>
</table>
Eurocode 3 flexural buckling example

**Comparison**

<table>
<thead>
<tr>
<th></th>
<th>EC 3-1-1: S235</th>
<th>EC 3-1-4: Austenitic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_y$ [N/mm²]</td>
<td></td>
<td>235</td>
</tr>
<tr>
<td>$\gamma_{M0}$ [-]</td>
<td>1,0</td>
<td>1,1</td>
</tr>
<tr>
<td>$\gamma_{M1}$ [-]</td>
<td>1,0</td>
<td>1,1</td>
</tr>
<tr>
<td>Cross-section $N_{c,Rd}$ [kN]</td>
<td>351</td>
<td>313</td>
</tr>
<tr>
<td>Stability $N_{b,Rd}$ [kN]</td>
<td>281</td>
<td>277</td>
</tr>
</tbody>
</table>

In this example, cs and ss show similar resistance to flexural buckling

⇒ **benefits** of strain hardening not apparent

EC3 1-4 doesn’t take duly account for strain hardening
Lateral torsional buckling

- Can be discounted when:
  - Minor axis bending
  - CHS, SHS, circular or square bar
  - Fully laterally restrained beams
  - $\lambda_{LT} < 0.4$
The design approach for lateral torsional buckling is analogous to the column buckling treatment.

- **Material yielding** (in-plane bending)
- **Elastic member buckling** $M_{cr}$
- **Yielding**
- **Buckling**

Non-dimensional slenderness $\bar{\lambda}_{LT}$
Lateral torsional buckling

- The design buckling resistance $M_{b,Rd}$ of a laterally unrestrained beam (or segment of beam) should be taken as:

\[
M_{b,Rd} = \chi_{LT} W_y \frac{f_y}{\gamma_{M1}}
\]

Reduction factor for LTB
Lateral torsional buckling

- Lateral torsional buckling curves are given below:

\[ \chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \lambda_{LT}^2}} \quad \text{but} \quad \chi_{LT} \leq 1.0 \]

\[ \Phi_{LT} = 0.5[ 1 + \alpha_{LT} (\bar{\lambda}_{LT} - 0.4) + \bar{\lambda}_{LT}^2 ] \]

Imperfection factor
Plateau length
Eurocode 3 Lateral torsional buckling curves
Non-dimensional slenderness

- Lateral torsional buckling slenderness:

\[ \lambda_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}} \]

- Buckling curves as for compression (except curve \( a_0 \))

- \( W_y \) depends on section classification

- \( M_{cr} \) is the elastic critical LTB moment
Eurocode 3 Lateral torsional buckling example

- I-shaped beam submitted to bending

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbon steel</th>
<th>Duplex stainless steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_y [N/mm²]</td>
<td>355</td>
<td>450</td>
</tr>
<tr>
<td>E [N/mm²]</td>
<td>210000</td>
<td>200000</td>
</tr>
</tbody>
</table>
Eurocode 3 Lateral torsional buckling example

**EC 3-1-1: S355**

- Classification

  \[ \varepsilon = \sqrt{\frac{235}{f_y}} = 0.81 \]

  - Flange
    \[ \frac{c}{t} = 6.78 < 7.3 = 9\varepsilon \]
    Class 1
  - Web
    \[ \frac{c}{t} = 45.3 < 58.3 = 72\varepsilon \]
    Class 1

  Cross-section = class 1

**EC 3-1-4: Duplex**

- Classification

  \[ \varepsilon = \sqrt{\frac{235}{f_y} \frac{E}{210000}} = 0.71 \]

  - Flange
    \[ \frac{c}{t} = 6.78 < 7.76 = 11\varepsilon \]
    Class 3
  - Web
    \[ \frac{c}{t} = 45.3 < 58.3 = 72\varepsilon \]
    Class 3

  Cross-section = class 3
Eurocode 3 Lateral torsional buckling example

**EC 3-1-1: S355**

- Ultimate moment
  - *Class 1*
    \[ M_{c,Rd} = \frac{W_{pl \cdot f_y}}{\gamma_{M0}} = 196 \text{ kNm} \]

**EC 3-1-4: Duplex**

- Ultimate moment
  - *Class 3*
    \[ M_{c,Rd} = \frac{W_{el \cdot f_y}}{\gamma_{M0}} = 202 \text{ kNm} \]

**Revision EC 3-1-4:**

- Classification limits: closer to carbon steel
  - Cross-section = class 2
    \[ M_{c,Rd} = \frac{W_{pl \cdot f_y}}{\gamma_{M0}} = 226 \text{ kNm} \]
Eurocode 3 Lateral torsional buckling example

Elastic critical buckling moment:

\[
M_{cr} = C_1 \frac{\pi^2 EI_z}{(k_zL)^2} \left\{ \sqrt{\left( \frac{k_z}{k_\omega} \right)^2 \frac{I_\omega}{I_z} + \frac{(k_zL)^2 GI_T}{\pi^2 EI_z} + \left( C_2z_g \right)^2} \right\} - C_2z_g
\]

<table>
<thead>
<tr>
<th></th>
<th>EC 3-1-1: S355</th>
<th>EC 3-1-4: duplex</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1) [-]</td>
<td>1,04</td>
<td>1,04</td>
</tr>
<tr>
<td>(C_2) [-]</td>
<td>0,42</td>
<td>0,42</td>
</tr>
<tr>
<td>(k_z) [-]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(k_\omega) [-]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(z_g) [mm]</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>(I_z) [mm(^4)]</td>
<td>5,6.10(^6)</td>
<td>5,6.10(^6)</td>
</tr>
<tr>
<td>(I_T) [mm(^4)]</td>
<td>1,2.10(^5)</td>
<td>1,2.10(^5)</td>
</tr>
<tr>
<td>(I_w) [mm(^6)]</td>
<td>1,2.10(^{11})</td>
<td>1,2.10(^{11})</td>
</tr>
<tr>
<td>(E) [MPa]</td>
<td>210000</td>
<td>200000</td>
</tr>
<tr>
<td>(G) [MPa]</td>
<td>81000</td>
<td>77000</td>
</tr>
<tr>
<td>(M_{cr}) [kNm]</td>
<td>215</td>
<td>205</td>
</tr>
</tbody>
</table>
# Eurocode 3 Lateral torsional buckling example

## Lateral torsional buckling resistance

<table>
<thead>
<tr>
<th></th>
<th>EC 3-1-1: S355</th>
<th>EC 3-1-4: Duplex</th>
<th>EC 3-1-4: Future revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_y$ [mm$^3$]</td>
<td>$5,5 \times 10^5$</td>
<td>$4,9 \times 10^5$</td>
<td>$5,5 \times 10^5$</td>
</tr>
<tr>
<td>$f_y$ [N/mm$^2$]</td>
<td>355</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>$M_{cr}$ [kNm]</td>
<td>215</td>
<td>205</td>
<td>205</td>
</tr>
<tr>
<td>$\bar{\lambda}_{LT}$ [-]</td>
<td>0,96</td>
<td>1,04</td>
<td>1,10</td>
</tr>
<tr>
<td>$\alpha_{LT}$ [-]</td>
<td>0,49</td>
<td>0,76</td>
<td>0,76</td>
</tr>
<tr>
<td>$\bar{\lambda}_{LT,0}$ [-]</td>
<td>0,2</td>
<td>0,4</td>
<td>0,4</td>
</tr>
<tr>
<td>$\phi_{LT}$ [-]</td>
<td>1,14</td>
<td>1,29</td>
<td>1,37</td>
</tr>
<tr>
<td>$\chi_{LT}$ [-]</td>
<td>0,57</td>
<td>0,49</td>
<td>0,46</td>
</tr>
<tr>
<td>$\gamma_{M1}$ [-]</td>
<td>1,0</td>
<td>1,1</td>
<td>1,1</td>
</tr>
<tr>
<td>$M_{b,Rd}$ [kNm]</td>
<td>111</td>
<td>99</td>
<td>103</td>
</tr>
</tbody>
</table>
Eurocode 3 Lateral torsional buckling example

- **Comparison**

<table>
<thead>
<tr>
<th></th>
<th>EC 3-1-1: S355</th>
<th>EC 3-1-4: Duplex</th>
<th>EC 3-1-4: Future revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_y$ [N/mm²]</td>
<td>355</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>$\gamma_{M0}$ [-]</td>
<td>1,0</td>
<td>1,1</td>
<td>1,1</td>
</tr>
<tr>
<td>$\gamma_{M1}$ [-]</td>
<td>1,0</td>
<td>1,1</td>
<td>1,1</td>
</tr>
<tr>
<td>Cross-section $M_{c,Rd}$</td>
<td>196</td>
<td>202</td>
<td>226</td>
</tr>
<tr>
<td>Stability $M_{b,Rd}$</td>
<td>111</td>
<td>99</td>
<td>103</td>
</tr>
</tbody>
</table>

- In this example, cs and ss show similar resistance to LTB
- However: Current tests and literature show that the EC3-1-4 results should be adapted to be closer to reality
  ⇒ too conservative
  (This will be shown in the example on finite element methods)
Section 4

Alternative methods
Alternative methods

- Direct strength method (DSM)
  - Part of the American code
  - For thin-walled profiles

- Continuous strength method (CSM)
  - Includes the beneficial effects of strain hardening

- Finite element methods
  - More tedious
  - Can include all the specificities of the model
Direct strength method

- AISI Appendix 1
- Very simple and straightforward method
- Used for thin-walled sections

- But requires an “Elastic buckling analysis”
  - Theoretical method provided in the literature
  - Finite strip method (for example CUFSM)
- More info: http://www.ce.jhu.edu/bschafer/
Direct strength method – example

- Lipped C-channel submitted to compression
  - Simply supported column
  - Column length: 5m

<table>
<thead>
<tr>
<th>Ferritic stainless steel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>EN 1.4003</td>
</tr>
<tr>
<td>$f_y \text{ [N/mm}^2\text{]}$</td>
<td>280</td>
</tr>
<tr>
<td>$f_u \text{ [N/mm}^2\text{]}$</td>
<td>450</td>
</tr>
<tr>
<td>$E \text{ [N/mm}^2\text{]}$</td>
<td>220000</td>
</tr>
</tbody>
</table>

![Diagram of lipped C-channel with dimensions]
Direct strength method example

- First step: Elastic buckling analysis
Direct strength method – example

- Output of the analysis = “Elastic critical buckling load”
  - In the example, the load factor from elastic buckling analysis equals:
    - For local buckling: 0,80
    - For distortional buckling: 1,26
    - For global buckling: 0,28

- Second step: Calculation of the nominal strengths for
  - Local buckling ⇒ one equation
  - Distortional buckling ⇒ one equation
  - Global buckling ⇒ one equation
Direct strength method example

- Nominal global buckling strength $P_{ne}$
  - $\lambda_c = \sqrt{P_y/P_{cre}} = 1.88$
  - $P_y = Af_y = 376 \text{ kN}$
  - $P_{cre} = 0.28 \times 376 = 107 \text{ kN}$

For $\lambda_c \leq 1.5$ \hspace{1cm} $P_{ne} = \left(0.658 \frac{\lambda_c^2}{\lambda_c^2}\right) P_y$

For $\lambda_c > 1.5$ \hspace{1cm} $P_{ne} = \left(\frac{0.877}{\lambda_c^2}\right) P_y$

- $P_{ne} = 93.81 \text{ kN}$
Direct strength method example

- Nominal local buckling strength $P_{nl}$
  - $\lambda_l = \sqrt{P_{ne}/P_{crl}} = 0.56$
  - $P_{crl} = 0.80 \times 376 = 302 \text{ kN}$

For $\lambda_l \leq 0.776$ \hspace{1cm} $P_{nl} = P_{ne}$

For $\lambda_l > 0.776$ \hspace{1cm} $P_{nl} = \left[1 - 0.15 \left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right] \left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne}$

- $P_{nl} = 93.81 \text{ kN}$
Direct strength method example

- Nominal distortional buckling strength $P_{nd}$
  - $\lambda_d = \sqrt{P_y / P_{crd}} = 0.89$
  - $P_{crd} = 1.26 * 376 = 473 \text{ kN}$

For $\lambda_d \leq 0.561$

$$P_{nd} = P_y$$

For $\lambda_d > 0.561$

$$P_{nd} = \left[ 1 - 0.25 \left( \frac{P_{crd}}{P_y} \right)^{0.6} \right] \left( \frac{P_{crd}}{P_y} \right)^{0.6} P_y$$

- $P_{nd} = 344.56 \text{ kN}$
Direct strength method – example

- Third step: The axial resistance is “just” the minimum of the three nominal strengths
  
  - Local: $P_{nl} = 93,81$ kN
  - Distortional: $P_{nd} = 344,56$ kN
  - Global: $P_{ne} = 93,81$ kN

  $\Rightarrow P_n = 93,81$ kN
Continuous strength method

- Stainless steel material characteristics:
  - Non-linear material model
  - High train hardening
  - Conventional design methods not able to take into account the full potential of the cross-section

The Continuous strength method uses a material model which includes strain hardening
Continuous strength method

- Material model considered in the CSM:

![Stress-strain curve](image)

- **Ramberg-Osgood model**
- **CSM model**

**Key Points**:
- $f_y$: Yield strength
- $f_u$: Ultimate strength
- $\varepsilon_y$: Yield strain
- $0.002\varepsilon_u$, $0.1\varepsilon_u$, $15\varepsilon_y$, $0.16\varepsilon_u$
Continuous strength method

- Comparison between EC3 and CSM predictions versus tests:

In compression

In bending

The CSM is able to accurately capture the cross-section behaviour
CSM: Flexural buckling example

- Cold formed rectangular hollow section submitted to concentric compression (example of slide 51)

<table>
<thead>
<tr>
<th>Material</th>
<th>EN 1.4301</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_y ) [N/mm²]</td>
<td>230</td>
</tr>
<tr>
<td>( E ) [N/mm²]</td>
<td>200000</td>
</tr>
</tbody>
</table>

Austenitic stainless steel
CSM: flexural buckling example

\[ f_y = 230 \text{N/mm}^2 \]
\[ E = 200000 \text{N/mm}^2 \]
\[ \varepsilon_y = \frac{f_y}{E} = 0.0012 \]

\[ f_u = 540 \text{N/mm}^2 \]
\[ 0.16\varepsilon_u = 0.16(1 - \frac{f_y}{f_u}) = 0.0919 \]
\[ E_{sh} = \frac{f_u - f_y}{0.16\varepsilon_u - \varepsilon_y} = 3418 \text{N/mm}^2 \]
CSM: flexural buckling example

\[ f_y = 230 \, \text{N/mm}^2 \]
\[ E = 200000 \, \text{N/mm}^2 \]
\[ \varepsilon_y = \frac{f_y}{E} = 0.0012 \]
\[ f_u = 540 \, \text{N/mm}^2 \]
\[ 0.16\varepsilon_u = 0.16(1 - \frac{f_y}{f_u}) = 0.0919 \]
\[ E_{sh} = \frac{f_u - f_y}{0.16\varepsilon_u - \varepsilon_y} = 3418 \, \text{N/mm}^2 \]
CSM: flexural buckling example

- \( \bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr,cs}}} = 0.60 \)
  - \( \sigma_{cr,cs} \) = elastic buckling stress of the full cross-section allowing for element interaction

- \( \frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}} = 5.27 \)

- \( f_{csm} = f_y + E_{sh} \varepsilon_y \left( \frac{\varepsilon_{csm}}{\varepsilon_y} - 1 \right) = 247 \frac{N}{mm^2} \)

- \( N_{c,Rd} = \frac{Af_{csm}}{\gamma_{M0}} = 335 \text{ kN} \)
CSM: flexural buckling example

- \( \bar{\lambda} = \sqrt{\frac{Af_{csm}}{N_{cr}}} = 0,60 \)
- \( N_{b,Rd} = \chi \frac{Af_{csm}}{\gamma_{M1}} = 294 \text{ kN} \)

<table>
<thead>
<tr>
<th></th>
<th>EC 3-1-1: S235</th>
<th>CSM: Austenitic</th>
<th>EC 3-1-4: Austenitic</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_y ) [N/mm²]</td>
<td>235</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>( \gamma_{M0} ) [-]</td>
<td>1,0</td>
<td>1,1</td>
<td>1,1</td>
</tr>
<tr>
<td>( \gamma_{M1} ) [-]</td>
<td>1,0</td>
<td>1,1</td>
<td>1,1</td>
</tr>
<tr>
<td>Cross-section ( N_{c,Rd} ) [kN]</td>
<td>351</td>
<td>335</td>
<td>313</td>
</tr>
<tr>
<td>Stability ( N_{b,Rd} ) [kN]</td>
<td>281</td>
<td>294</td>
<td>277</td>
</tr>
</tbody>
</table>
Finite element model

- The material stress-strain curve can be accurately modeled (for example by using Ramberg-osgood material law or “real” measured tensile coupon tests results)

Two-stage Ramberg-Osgood model:

\[
\varepsilon = \begin{cases} 
\frac{\sigma}{E_0} + 0.002 \left( \frac{\sigma}{\sigma_{0.2}} \right)^n & \sigma \leq \sigma_{0.2} \\
\varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u \left( \frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}} \right)^m & \sigma > \sigma_{0.2}
\end{cases}
\]
Finite element model

The nonlinear parameters are given by the following expressions (according to Rasmussen’s revision):

\[
\begin{align*}
n &= \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \\
m &= 1 + 3.5 \frac{\sigma_{0.2}}{\sigma_u} \\
E_{0.2} &= \frac{E_0}{1 + 0.002n \frac{E_0}{\sigma_{0.2}}} \\
\varepsilon_u &= 1 - \frac{\sigma_{0.2}}{\sigma_u} \\
\frac{\sigma_{0.2}}{\sigma_u} &= \begin{cases} 
0.2 + 185 \frac{\sigma_{0.2}}{E_0} & \text{for austenitic and duplex} \\
0.2 + 185 \frac{\sigma_{0.2}}{E_0} & \text{for all stainless steel alloys}
\end{cases}
\end{align*}
\]
Finite element model

- I-shaped beam submitted to bending suffering lateral torsional buckling: all imperfections can be modelled.
Finite element model

- The load-deflections curve can be calculated
  - Results: elastic behaviour and first yielding
Finite element model

- The load-deflections curve can be calculated
  - Results: instability phenomenon => Lateral torsional buckling
Finite element model

- The load-deflections curve can be calculated
  - Results: instability phenomenon => Lateral torsional buckling
Finite element model

- The load-deflections curve can be calculated
  - Results: post buckling behaviour
Finite element model

- The load-deflections curve can be calculated
  - Results: post buckling behaviour

![Graph showing load-deflections curve with vertical displacement (mm) on the x-axis and total load (kN) on the y-axis. The curve peaks around 350 kN and then decreases.](image)
Finite element model

Eurocode 3-1-4 material model

$M_{FE M}=231 \text{ kNm}$

$M_{b,Rd}=99 \text{ kNm}$
Finite element model

\[ M_{b,Rd} = 99 \text{ kNm} \]

Measured mat. parameters

\[ M_{FEM} = 270 \text{ kNm} \]

Eurocode 3-1-4 mat. model

\[ M_{FEM} = 231 \text{ kNm} \]

Eurocode 3-1-4
Section 5

Deflections
Deflections

- Non-linear stress-strain curve means that stiffness of stainless steel $\downarrow$ as stress $\uparrow$
- Deflections are slightly greater in stainless steel than in carbon steel
- Use secant modulus at the stress in the member at the serviceability limit state (SLS)
Deflections

Secant modulus $E_s$ for the stress in the member at the SLS
Deflections

Secant modulus ES determined from the Ramberg-Osgood model:

\[ E_S = \frac{E}{1 + 0.002 \frac{E}{f} \left( \frac{f}{f_y} \right)^n} \]

- \( f \) is stress at serviceability limit state
- \( n \) is a material constant
Deflections in an austenitic stainless steel beam

<table>
<thead>
<tr>
<th>Stress ratio $f/f_y$</th>
<th>Secant modulus, $E_s$ N/mm²</th>
<th>% increase in deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>200,000</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>192,000</td>
<td>4</td>
</tr>
<tr>
<td>0.7</td>
<td>158,000</td>
<td>27</td>
</tr>
</tbody>
</table>

$f = \text{stress at serviceability limit state}$
Section 6

Additional information
Response to seismic loading

- Higher ductility (austenitic ss) + sustains more load cycles
  → greater hysteretic energy dissipation under cyclic loading

- Higher work hardening
  → enhances development of large & deformable plastic zones

- Stronger strain rate dependency –
  → higher strength at fast strain rates
Design of bolted connections

- The strength and corrosion resistance of the bolts and parent material should be similar.
- Stainless steel bolts should be used to connect stainless steel members to avoid bimetallic corrosion.
- Stainless steel bolts can also be used to connect galvanized steel and aluminium members.
Design of bolted connections

- Rules for carbon steel bolts in clearance holes can generally be applied to stainless steel (tension, shear)
- Special rules for bearing resistance required to limit deformation due to high ductility of stainless steel

\[
f_{u,\text{red}} = 0.5f_y + 0.6f_u < f_u
\]
Preloaded bolts

Useful in structures like bridges, towers, masts etc when:

- the connection is subject to vibrating loads,
- slip between joining parts must be avoided,
- the applied load frequently changes from a positive to a negative value

- No design rules for stainless steel preloaded bolts
- Tests should always be carried out
Design of welded connections

- Carbon steel design rules can generally be applied to stainless steel.
- Use the correct consumable for the grade of stainless steel.
- Stainless steel can be welded to carbon steel, but special preparation is needed.
Fatigue strength

- Fatigue behaviour of welded joints is dominated by weld geometry

- Performance of austenitic and duplex stainless steel is at least as good as carbon steel

- Follow guidelines for carbon steel
Section 7

Resources for engineers
Resources for engineers

- Online Information Centre
- Case studies
- Design guides
- Design examples
- Software
A CENTURY OF INNOVATION

From small beginnings a hundred years ago, stainless steel has grown to be an integral part of our lives. Utilised primarily for its corrosion resistance, stainless steel is also found in applications where strength, innovation and aesthetics are important.
Stainless in Construction Information Centre

www.stainlessconstruction.com

Online Information Centre for Stainless Steel in Construction

Enter search query

Stainless steel at your fingertips...

This website will lead you to essential technical information about the use of stainless steel in construction.

Featured Resource:
Thames Gateway Water Treatment
12 Structural Case Studies

www.steel-stainless.org/CaseStudies
Design Guidance to Eurocodes

www.steel-stainless.org/designmanual
- Guidance
- Commentary
- Design examples

Online design software:
www.steel-stainless.org/software
Summary

- Structural performance: similar to carbon steel but some modifications needed due to non-linear stress-strain curve
- Design rules have been developed
- Resources (design guides, case studies, worked examples, software) are freely available!
References


- AISI Standard. North American specification Appendix 1: Design of Cold-Formed Steel Structural Members Using the Direct Strength Method. 2007


Thank You

Barbara Rossi – barbara.rossi@kuleuven.be
Maarten Fortan – maarten.fortan@kuleuven.be

Test your knowledge of stainless steel here:
https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 08
Stainless Steel Surfaces
Contents

1. Stainless steel finishes
2. Tridimensional Surfaces
3. Woven meshes
4. References
1 - Stainless steel finishes

- Mill Finishes
- Mechanically Polished and Brushed Finishes
- Patterned Finishes
- Bead Blasted Finishes
- Electro-Polished Finishes
- Coloured Finishes
- Electrolytically Coloured Finishes
- Electrolytically Coloured and Patterned Finishes
- Organic Coatings
- Specialist Decorative Finishes

Many finishes are available
Ex-mill cold rolled finishes ¹,³

EN 10088-2 cold rolled finishes from table 6 of the standard, with a guide to typical Ra values

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Finishing Process Route</th>
<th>Notes</th>
<th>Typical (Ra) μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B</td>
<td>Cold rolled, heat treated, pickled, skin passed</td>
<td>Most common 'cold rolled' finish available. Non-reflective, smooth finish, good flatness control. Thickness range limited by manufactures' skin passing rolling capacity.</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>2C</td>
<td>Cold rolled, heat treated, not descaled</td>
<td>Smooth with scale from heat treatment, suitable for parts to be machined or descaled in subsequent production or where the parts are for heat resisting applications.</td>
<td>-</td>
</tr>
<tr>
<td>2D</td>
<td>Cold rolled, heat treated, pickled</td>
<td>Thicker sheet size ranges. Smoothness not as good as 2B, but adequate for most purposes.</td>
<td>0.4-1.0</td>
</tr>
<tr>
<td>2E</td>
<td>Cold rolled, heat treated, mechanically descaled</td>
<td>Rough and dull. Usually applied to steels with a scale which is very resistant to pickling solutions</td>
<td>-</td>
</tr>
<tr>
<td>2H</td>
<td>Cold rolled, work hardened</td>
<td>&quot;Temper&quot; rolling on austenitic types improves mechanical strength. Smoothness similar to 2B</td>
<td>-</td>
</tr>
<tr>
<td>2R</td>
<td>Cold rolled, bright annealed</td>
<td>Highly reflective &quot;mirror&quot; finish, very smooth. Often supplied with plastic coatings for pressings. Manufactured items usually put into service without further finishing</td>
<td>0.05-0.1</td>
</tr>
<tr>
<td>2Q</td>
<td>Cold rolled, hardened and tempered, scale free</td>
<td>Only available on martensitic types (e.g. 420). Scaling avoided by protective atmosphere heat treatment or descaling after heat treatment</td>
<td>-</td>
</tr>
</tbody>
</table>

More on Ra:

These are the most common ones
Most common mill finishes

2B This is produced as 2D, but a final light rolling using highly polished rolls gives the surface a smooth, reflective, grey sheen. This is the most widely used surface finish in use today and forms the basis for most polished and brushed finishes.

2D This is achieved by cold rolling, heat treating and pickling. The low reflective matt surface appearance is suitable for industrial and engineering needs but, architecturally, is suitable for less critical aesthetic applications.

2R By bright annealing under Oxygen-free atmospheric conditions following cold rolling using polished rolls, a highly reflective finish, that will reflect clear images, is obtained. This ultra-smooth surface is less likely to harbour airborne contaminants or moisture than any other mill finish, and it is easy to clean.
**Special Finishes**

EN 10088-2 special finishes from Table 6 of the standard, with a guide to typical Ra

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Finishing Process Route</th>
<th>Notes</th>
<th>Typical (Ra) μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G or 2G</td>
<td>Ground</td>
<td>Can be based on either '1' or '2' ex-mill finishes*. A unidirectional texture, not very reflective</td>
<td>-</td>
</tr>
<tr>
<td>1J or 2J</td>
<td>Brushed or dull polished</td>
<td>Can be based on either '1' or '2' ex-mill finishes*. Smoother than &quot;G&quot; with a unidirectional texture, not very reflective</td>
<td>0.2-1.0</td>
</tr>
<tr>
<td>1K or 2K</td>
<td>Satin polished</td>
<td>Can be based on either '1' or '2' ex-mill finishes*. Smoothest of the special non-reflective finishes with corrosion resistance suitable for most external applications.</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>1P or 2P</td>
<td>Bright polished</td>
<td>Can be based on either '1' or '2' ex-mill finishes*. Mechanically polished reflective finish. Can be a mirror finish.</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>2F</td>
<td>Cold rolled, heat treated, skin passed on roughened rolls</td>
<td>Uniform non-reflective matt surface, can be based on either 2B or 2R mill finishes</td>
<td>-</td>
</tr>
<tr>
<td>1M or 2M</td>
<td>Patterned</td>
<td>Can be based on either '1' or '2' ex-mill finishes*. One side patterned only. Includes &quot;chequer&quot; plates (&quot;1&quot; ex-mill finish) &amp; fine textures finishes (&quot;2&quot; ex-mill finish)</td>
<td>-</td>
</tr>
<tr>
<td>2W</td>
<td>Corrugated</td>
<td>Profile rolled (e.g. trapezoidal or sinusoidal shapes)</td>
<td>-</td>
</tr>
<tr>
<td>2L</td>
<td>Coloured</td>
<td>Applied to flat (2R, 2P or 2K type fishes) or patterned (2M) sheet base finishes in a range of colours</td>
<td>-</td>
</tr>
<tr>
<td>1S or 2S</td>
<td>Surface coated</td>
<td>Can be based on either '1' or '2' ex-mill finishes. Normally coated on one side only with a metallic coating, such as tin, aluminium or titanium</td>
<td>-</td>
</tr>
</tbody>
</table>

* 1 finishes are for hot-rolled products, 2 finishes for cold rolled

There is a very wide choice of special finishes
Patterned Finishes $^{4,5,7}$

These few examples illustrate the use of sheets patterned on one side only, classified as 2M. A wide variety of patterns are available.
Coloured finishes\textsuperscript{4, 5,7}

This is only a selection of the colour effects that can be produced by electrolytically colouring stainless steel
Etched Patterns$^{4,5,7}$

Silk screen and photoresist processes have been developed to transfer any pattern onto stainless steel, the surface of which is then acid etched to reveal the pattern. Acid etching is a process which removes a small amount of surface material. Etched surfaces have a dull and a slightly coarse appearance which contrast well with polished or satin finished un-etched surfaces. Electro-chemical colour can be given to etched surfaces before or after etching.
Proprietary finishes\textsuperscript{4,5}
Many specific & custom finishes are available from specialized companies
Some examples are shown below
Electropolishing

Produces bright reflecting surfaces which feature
- Optimum corrosion resistance for any grade
- Easier disinfection and cleanability
- Easier removal of graffiti

However
- Irregular surfaces are more visible
- As well as damage from scratches and mechanical damage
Bead Blasting

The appearance can be altered by different blasting materials, e.g. glass bead (above) or shredded glass (below)
Please note:

There are many different grades of stainless steel, which offer solutions to a wide range of design problems, from corrosion resistance in even the most aggressive environments, to high strength requirements; and from ease of formability to ease of welding. Similarly, stainless steels offer a wide range of surface finishes which can assist the architect in achieving the aesthetically pleasing appearance he is looking for. Surface finishes range from a plain matte through soft polishing through textured patterns and colours right up to highly polished mirror finishes. These provide the imaginative designer with a wide array of options.

Care should be taken when using glossy surface finishes to ensure that they do not unwittingly create glare or heat reflectivity issues. Especially building fronts facing the sun and concave-shaped areas deserve special attention during the planning phase.
Architects use everyday the palette of surface finishes available on stainless steels. In Chapter 2 you will find some examples of buildings for which the surface finish is essential to the aesthetics.
2 - Tridimensional Finishes

i.e. deeper tridimensional features than patterns obtained by embossing, punching, cutting, profiling, ....

usually carried out on Computer-controlled machines
Embossed patterns$^9$
Irregular shapes\(^9\) (fluid forming)
Perforated sheet\textsuperscript{9}
Semi-transparent glass panels with perforated sheet

*Figure showing semi-transparent glass panels with perforated sheet.*
Expanded Sheet
Combination of techniques 11

Stockholm Waterfront Building: Perforated and colored stainless steel ceiling that reproduces the image of the melting ice on the lower right.
3 – Woven Mesh
Standard 12-14

A very wide set of woven shapes and patterns is available, with adjustable

- stiffness
- open area
- light diffusion
- acoustic transparency
- color
- etc...
Example of decoration with stainless steel mesh
Outside decoration with Stainless Wire mesh

Stainless wire mesh is widely used for decoration. It allows special effects such as lights (with LEDs) as shown (Swarovski Building headquarters)
Woven stainless with LEDs $^{13}$
4 - References and sources

1. https://www.worldstainless.org/Files/issf/non-image-files/PDF/Euro_Inox/Finishes02_EN.pdf
5. http://www.poligrat.de/home/
11. http://cambridgearchitectural.com
12. https://gkd.de/architekturgewebe/
Thank you

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 09
Joining & Fabrication of Stainless Steels
Contents

1. Joining
2. Fabrication
## 1 - Joining

### Applicable joining processes: all of them!

<table>
<thead>
<tr>
<th>Process (Refs)</th>
<th>Videos</th>
<th>Preferred process for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding (1-5)</td>
<td>MIG Welding</td>
<td>High strength of the joints</td>
</tr>
<tr>
<td>(widely used)</td>
<td>TIG Welding</td>
<td>No dismantling</td>
</tr>
<tr>
<td></td>
<td>Welding robot</td>
<td></td>
</tr>
<tr>
<td>Fastening (widely used)</td>
<td>Webinar</td>
<td>Easy on-site assembly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assembling dissimilar materials (wood, glass...)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dismantling at a later stage</td>
</tr>
<tr>
<td>Brazing/Soldering</td>
<td>Soldering</td>
<td>Water tightness (Used mostly in roofing)</td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Press-fitting</td>
<td>Press-fit_example</td>
<td>Permanent joining of tubes</td>
</tr>
<tr>
<td>Folding</td>
<td></td>
<td>Water tightness</td>
</tr>
<tr>
<td>Other ....</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adhesive Bonding</td>
<td></td>
<td>Surface finish integrity</td>
</tr>
<tr>
<td>(not used often,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>but growing)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Arc Welding

Advantages of arc welding

- weld properties equal to that of annealed condition
- provides the strongest joints
- can be done on site or in the shop
- joins thin and thick material of any shape
- joins similar or dissimilar metals (usually carbon steel with proper choice of filler material)
- resists fatigue and cyclic loads
- same corrosion and heat resistance as the annealed base metal

Limitations of arc welding

- not possible with all grades
- require qualified operators and procedures
- may cause heat-induced distortions
- post-weld finishing operations are required for a good-looking finish (such as sand blasting)
- loss of mechanical properties in case of cold-worked material
Arc Welding

Video: polishing a weld
Mechanical fastening

Advantages of mechanical fastening
- Can be dismantled
- Ideal for on-site building
- Fast
- No need of qualified operators

Limitations of mechanical fastening
- Not as strong as welds
- May cause crevice corrosion (see corrosion resistance chapter)

Selecting the appropriate fastener:
The German Institute for Building Technology* has issued recommendations for the selection of fasteners according to the environment. Please read Reference 4, Table 1a (exposure classes) and Table 8 (stainless grades by class)

* Deutsches Institut für Bautechnik (DIBt)
Press fitting
(a process used for tubes only)

Advantages of press fitting
- Perfectly tight for liquid and gases
- Fast
- No flame
- Perfectly clean surfaces
- No need of qualified operators

Limitations of press fitting
- Cannot be dismantled
- Require sleeves for each tube diameter
Adhesive Bonding

Advantages of adhesive bonding

- makes a joint almost invisible, enhancing product appearance
- provides uniform distribution of stress and a greater stress-bearing area
- joins thin and thick material of any shape
- joins similar or dissimilar materials
- minimizes or prevents electrochemical (galvanic) corrosion between dissimilar materials
- resists fatigue and cyclic loads
- provides joints with smooth contours
- seals joints against a variety of environments
- insulates against heat transfer and electrical conductance
- is free from heat-induced distortions
- dampens vibrations and absorb shocks
- provides attractive strength/weight ratio
- is frequently faster or cheaper than mechanical fastening

Limitations of adhesive bonding

- does not permit visual examination of the bond area
- requires careful surface preparation, often with corrosive chemicals
- may involve long cure times, particularly where high cure temperatures are not used
- may require holding fixtures, presses, ovens and autoclaves, not usually needed for other fastening methods
- should not be exposed to service temperatures above approximately 180 °C
- requires rigid process control, including emphasis on cleanliness, for most adhesives
- depends on the environment to which it is exposed
Adhesive bonding applications

Attaching of banister elements *(Delo-Duopox AD895)*
- Fills gaps, suitable for small and large bonding gaps
- Good chemical resistance and aging resistance
- For interior and exterior use
- Efficiency: flexible modular system in banister construction. The additional process steps required for welding, such as grinding or polishing, are avoided

Stainless steel panels (Grade 1.4404) are attached to the outer walls of this 6-storey office building in Hannover (Germany) using an adhesive bonding system without the need for additional mechanical fastening.
Adhesive bonding is used for the assembly of door handles.

Adhesive bonding is a practical solution in building applications, when stainless steel has to be fastened to masonry or natural stone.

<table>
<thead>
<tr>
<th></th>
<th>With stainless steel</th>
<th>Silicone</th>
<th>Polymer modified with silane</th>
<th>Polyurethane</th>
<th>Acrylic</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Carbon steel/painted</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Carbon steel/galvanised</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Aluminium</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Wood</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Glass/ceramic</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Plastic PVC</td>
<td>yes</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Plastic PA</td>
<td>yes</td>
<td>○</td>
<td>●</td>
<td>X</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>Plastic PP/PE</td>
<td>no</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

● highly recommendable - ○ recommendable - X not recommendable

Table 1. Selection of adhesives for structural bonding [11]
References on Joining

1. http://www.worldstainless.org/Files/issf/animations/WeldedFabrication/start_1.html
7. http://shura.shu.ac.uk/3115/
2 - Fabrication

Very comprehensive documents are available, see the list of references

Ref 1 is a training course dedicated to the fabrication of stainless steels

Chapter 2 lists a number of applications in architecture, building and construction: fabrication of all shapes and finishes is achieved routinely today
Videos on Processes

- Stainless Steel Melting and Rolling  
  https://www.youtube.com/watch?v=5zwgI-pQ6kE
- Shearing and Bending  
  https://www.youtube.com/watch?v=VMu7_W0QE3Y
- Water Jet Cutting  
- Deep Drawing  
  https://www.youtube.com/watch?v=n-ht_5Ysurc
- Wire Bending Machine  
  https://www.youtube.com/watch?v=kDoSDiiZx6U
- Spring Forming Machine  
  https://www.youtube.com/watch?v=SwY-RT4DBxY
- Roll Forming  
  https://www.youtube.com/watch?v=44XD5mZoM_0
- Machining (milling)  
  https://www.youtube.com/watch?v=LDxNDWObTyg

More videos are readily available on the net
References on Fabrication

Thank you

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 10

Forms and availability
Why « Forms and Availability » ?

- Delivery times and costs are major issues for architects & civil engineers
- While all stainless steel products start from a melting shop
  - There are many processing routes for stainless products
  - And stockholders, traders providing service packages
- And therefore Delivery times and Costs may vary widely
Some background information
How stainless steel is produced

- **Video**: Steelmaking and Hot Rolling of coils
- **Video**: Hot Rolling of coils
- **Video**: Cold rolling of coils
- **Video**: Steelmaking and hot rolling of bars
- **Video**: Wire rod rolling
- **Video**: Wire rod rolling
Stainless Steel Supply Chain

**Stainless Steel Mill**
- Ex-mill sales

**Distributors** (of which mill-owned)
- Customized:
  - Cut to length
  - Cut to shape
  - Polishing ...

**Products**
- Coils, Sheets, Plates
- Bars, Wire
- Reinforcing bar

**Service**
- Minimum weight: 1 slab
- Production on order
- Lead time: 2 – 3 weeks
- Lowest price / Kg
- Small orders
- Available from stock
- Short delivery times (1-3 days)
- Price premium for service

**Fabricators**
- + Specific finishes (such as color)

**Stainless Steel Mill**
- Standard Component Manufacturing

**Distributors** (of which mill-owned)
- Products
  - Fasteners
  - Tubes
  - Valves
  - Fittings
- Service
  - Available from stock
  - Short delivery times (1-3 days)
  - Price premium for service
Flat products

Ex-mill

Cold-rolled coil

Cold-rolled strip

Cold-Rolled polished sheet

Plates

I-beam from plate

Door & Window profiles

Standard tubes

Profiled tubes

Tube fittings

Custom

Laser cut shape

Clamps

Railings
## Long Products

**Ex-mill**
- **Bars**
- **Tie-bars**
- **Reinforcing Bar**
- **Cables**
- **Wire Rod**
- **Mesh**

**Custom**
- **Threaded bars**
- **Concrete Anchors**
- **Handles**
- **Fasteners**
- **Mesh shower curtain**
- **Sunbreaker**
Future trends

The urgency of climate change mitigation and of a sustainable economy will drive major changes in the years to come.

A new product offer is likely to appear:

- re-conditioned products. Stainless steel from buildings/facilities being de-constructed could be re-processed and made available for a new service life without loss of properties.

- Higher strength and thinner products, able to offer the same service performance with less material use. The development of lean duplex grades and of cold-worked austenitic grades is already taking place.
References

Major stainless steel producers
https://www.worldstainless.org/about-issf/issf-members/
Thank you

Test your knowledge of stainless steel here:
https://www.surveymonkey.com/r/3BVK2X6
Supporting presentation for lecturers of Architecture/Civil Engineering

Chapter 11
Sustainability of Stainless Steels
Definitions

- **Greenhouse Gas (GHG):** Emission Tonnes of CO2-eq /Tonne Steel \(^{(1)}\)
- **Global Warming Potential:** no unit Ratio of the abilities of different greenhouse gases (GHG) to trap heat in the atmosphere relative to that of carbon dioxide (CO2) \(^{(2)}\). For instance, the GWP of Methane is **28 over a 100-year period**. The primary GHG emitted in the steelmaking is CO2.
- **Primary Energy Consumption (GJ/T) GWP also called Energy Intensity:** The energy consumption required to produce 1 tonne of primary material (such as steel). \(^{(1)}\)
- **Gross Energy Requirement (GER):** is the total amount of energy required for a product. \(^{(8)}\)
- **Materials Efficiency:** Measures the amount of material not sent for permanent disposal, landfill or incineration, relative to crude steel production. \(^{(1)}\)
Definitions

- **Life Cycle Inventory (LCI):** a structured, comprehensive and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with the entire life cycle of products. \(^{(3)}\)

- **Life Cycle Cost (LCC):** is a tool for assessing the total cost performance of an asset over time, including the acquisition, operating, maintenance, and disposal costs. \(^{(4)}\)

- **Life Cycle Assessment (LCA):** is a tool to assist with the quantification and evaluation of environmental burdens and impacts associated with product systems and activities, from the extraction of raw materials in the earth to end-of-life and waste disposal. The tool is increasingly used by industries, governments, and environmental groups to assist with decision-making for environment-related strategies and materials selection.
Definitions

Safety Indicators:

- **Lost–Time Injury**: The lost time injury frequency rate is the number of lost time injuries for each 1,000,000 working hours. \(^{(1)}\)

Recycling Indicators:

- **Recycling rate** how much of the end-of-life (EOL) material is collected and enters the recycling chain (as opposed to material that is landfilled). \(^{(5)}\)

- **Recycled content** is defined as the proportion, by mass, of post-consumer and pre-consumer recycled material in a product. \(^{(6)}\)

- **Solid Waste Burden (SWB)**: includes mining waste, tailings, slag and power station ash
Comments on Indicators:

The recycling indicators do not take into account «downcycling».

 Metals can be recycled without loss of quality. Because metallic bonds are restored upon resolidification, metals continually recover their original performance properties, even after multiple recycling loops. This allows them to be used again and again for the same application. By contrast, the performance characteristics of most non-metallic materials degrade after recycling.  

45
Downcycling is better than waste but still a long way from Circular Economy \(^{(46,47)}\)

Circular economy is all about closing resource loops, mimicking natural ecosystems in the way we organize our society and businesses.
Sustainability

“Sustainability concerns the whole cycle of a product construction i.e. from raw material acquisition, through planning, design, construction and operations, to final demolition and waste management.” (Rossi, B. 2012)
Sustainability of stainless steel:

1. Environmental
2. Social
3. Economic
1. Environmental Production $\Rightarrow$ Use $\Rightarrow$ Recycling \textsuperscript{15}

Life cycle of stainless steel in 2010. (YaleUniversity/ISSF stainless steel project 2013)
More on Use and Recycling ¹⁵, ²³-²⁵

<table>
<thead>
<tr>
<th>End Use Sector</th>
<th>Average lifetime (in years)</th>
<th>To landfill</th>
<th>Collected for recycling</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>As stainless steel</td>
<td>As carbon steel</td>
</tr>
<tr>
<td>Building and infrastructure</td>
<td>50</td>
<td>8%</td>
<td>92%</td>
<td>95%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Transportation (passenger cars)</td>
<td>14</td>
<td>13%</td>
<td>87%</td>
<td>85%</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Transportation (others)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial Machinery</td>
<td>25</td>
<td>8%</td>
<td>92%</td>
<td>95%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Household Appliances and Electronics</td>
<td>15</td>
<td>30%</td>
<td>70%</td>
<td>95%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Metal Goods</td>
<td>15</td>
<td>40%</td>
<td>60%</td>
<td>80%</td>
<td>20%</td>
<td></td>
</tr>
</tbody>
</table>
GHG Emissions vs. Recycled content

* The recycled content is limited by scrap availability
Sustainability of Stainless Steels

Recycled content of stainless steel
Greenhouse Gas Emissions for Stainless steel\(^{(15)}\)

3.3 ton CO\(_2\)/ton Stainless Steel\(^{(16)}\)

Breakdown of emissions:
- Raw Materials: \(~58\%\)
- Electricity Generation: \(~19\%\)
- Steelmaking: \(~15\%\) \(^{(17)}\)

Note: This does not take into account Nickel produced by the Nickel Pig Iron Route, for which the figure for Ni is believed to be about 3 times higher. China is currently the only country using Nickel Pig iron.
Primary Energy Demand\(^{18}\)

* The recycled content is limited by scrap availability
Environmental impacts for “cradle-to-gate” metal production

<table>
<thead>
<tr>
<th>Metal</th>
<th>Process</th>
<th>GER (MJ/kg)</th>
<th>GWP (kg CO₂e/kg)</th>
<th>AP (kg SO₂e/kg)</th>
<th>SWB (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>Electric furnace and Argon – Oxygen Decarburization</td>
<td>75</td>
<td>6.8</td>
<td>0.051</td>
<td>6.4</td>
</tr>
<tr>
<td>Steel</td>
<td>Integrated route (BF and BOF)</td>
<td>23</td>
<td>2.3</td>
<td>0.020</td>
<td>2.4</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Bayer refining, Hall-Heroult smelting</td>
<td>361</td>
<td>35.7</td>
<td>0.230</td>
<td>16.9</td>
</tr>
<tr>
<td>Copper</td>
<td>Smelting/convertting and electro-refining</td>
<td>33</td>
<td>3.3</td>
<td>0.040</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Heap leaching and SX/EW</td>
<td>64</td>
<td>6.2</td>
<td>-</td>
<td>125</td>
</tr>
</tbody>
</table>

GER: Gross Energy Requirement  
GWP: Global Warming Potential  
AP: Acidification Potential  
SWB: Solid Wast Burden
Environmental impacts for “cradle-to-gate” metal production\textsuperscript{20}

Gross Energy Requirement for “cradle-to-gate” production of various metals

Global Warming Potential for “cradle-to-gate” production of various metals

(without any recycled content)
Materials are not used in the same quantity for a similar function or service\textsuperscript{21}

Example:
Indicative environmental potential impacts for 3 different wall finishes.

<table>
<thead>
<tr>
<th>Material</th>
<th>PED (MJ/m\textsuperscript{2})</th>
<th>GWP (Kg CO\textsubscript{2}-eq./m\textsuperscript{2})</th>
<th>End-of-Life (EOL) scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pressure laminate such as Trespa\textsuperset{®}</td>
<td>759.3</td>
<td>23.9</td>
<td>50% reuse + 50% landfill</td>
</tr>
<tr>
<td>Generic stucco</td>
<td>144.2</td>
<td>12.7</td>
<td>Not recycled</td>
</tr>
<tr>
<td>Stainless Steel 0.5 mm</td>
<td>140.5</td>
<td>7.2</td>
<td>RR = 95%</td>
</tr>
<tr>
<td>Stainless Steel 0.8 mm</td>
<td>191.7</td>
<td>11.3</td>
<td>RR = 95%</td>
</tr>
</tbody>
</table>
Materials Efficiency

Reduce:
the quantity of raw material to produce Stainless Steel. (40%), consequently the CO2 emission decreases.

Reuse:
The durability of stainless steels makes reuse very important.
Examples: Bottles, mugs, cups, straws...
Single use of plastics is increasingly banned
Example: Reuse

The Stainless Steel panels had become dirty and scratched after about 50 years use. During renovation of the lobby, the 50-year old stainless steel panels were removed, cleaned, refinished and reused.
Recycle:
Stainless Steel is 100% recyclable, all the scrap collected (82%) is reused.
Zero-waste stainless steel production ⇒ Slag and dust are the main by-products and waste which result from steelmaking. Example: Slag products can be used in the asphalt for road construction.
LEED* and Stainless LCI Data

  - New version includes changes that are favorable to stainless:
    - Greater emphasis on service life
    - Tighter requirements on VOC** emissions (a problem for some materials such as plastics)
- U.S. General Services Administration (manages US government buildings and properties) recently endorsed the use of LEED
  - State and local governments increasingly require LEED or similar certifications for new buildings or modifications

** VOC: Volatile Organic Compounds: for Stainless Steel, very small emissions during processing & fabrication (no data available yet) and none during use
Sustainable building with Stainless steel - The David L. Lawrence Convention Center, Pittsburgh (2003)  

Stainless steel roof:

- S30400 stainless steel
- Measuring: 280 × 96m
- Sheathed with 23,000m² of 0.6mm (24-gauge), weighing about 136 tonnes.
Sustainable building with Stainless steel: the Gold LEED status

The Gold **LEED** (Leadership in Energy and Environment Design) status recognizes:

- the centre’s brownfield redevelopment
- accommodation of alternative transportation
- reduced water use
- efficient energy performance
- use of materials that emit no or low amounts of toxins
- innovative design
Sustainable Civil Works with Stainless: 
The Progreso Pier (27)

At Progreso, Mexico, a pier was built in 1970. The marine environment made the carbon steel rebar corrode – the structure failed.
Sustainable Civil Works with Stainless:
The Progreso Pier

The neighbouring pier had been erected in 1937 – 1941 using stainless steel reinforcement.
Sustainable Civil Works with Stainless: The Progreso Pier

Ever since then, it has been maintenance free and remained in pristine condition.
2. Social

A sustainable material does not harm the people working to produce it, or who handle it during its use, recycling and ultimate disposal.

- Stainless steel is not harmful to people during either its production or use. For these reasons, stainless steels are the primary material in medical, foodprocessing, household and catering applications.

- The safety like injury-free and healthy workplace of the employees is the key priority for the stainless steel industry.

- Stainless steel also improves the quality of life by making technical advances possible. For example the installations that provide us with clean drinking water, food and medication would not be nearly as hygienic and efficient as they are without stainless steel.
3. Economic

- 300,000 People directly or indirectly employed in the stainless steel industry worldwide
- US$130 billion Turnover of the global stainless industry, 2010
- 5.85% average increase in production each year since 1970
- 100% recyclable forever
- 45 million tonnes stainless steel fabricated in 2016
Life Cycle Costing (LCC) \[30\]

- LCC is the cost of an asset throughout its life cycle, while fulfilling the performance requirements (ISO 15686-5).
- LCC is the sum of all cost related to a product incurred during the life cycle:

  conception $\Rightarrow$ fabrication $\Rightarrow$ operation $\Rightarrow$ end-of-life
LCC is a mathematical procedure helping to make investment decisions and/or compare different investment options.

\[
LCC = AC + IC + \sum_{n=1}^{N} \frac{OC}{(1+i)^n} + \sum_{n=1}^{N} \frac{LP}{(1+i)^n} + \sum_{n=1}^{N} \frac{RC}{(1+i)^n}
\]

Where: 
- \( N \) = Desired service life 
- \( i \) = Real interest rate 
- \( n \) = Year of the event
Stainless steel is not expensive if the life cycle cost is taken into account. The cost of other materials substantially increases over time while the cost of stainless steel normally remains constant.

“Corrosion of metals costs the United States economy over $300 billion annually. It is estimated that about one-third of this cost ($100 billion) is avoidable by use of best known technology. This begins with design, selection of anti-corrosion materials like stainless steel, and quantifying initial and future costs including maintenance by Life Cycle Costing/LCC techniques.”
LCC Example: Bridges

Example of stainless steel bridge life cycle phases and its impacts on the environment in different areas of the world.
### LCC Example: Bridge
Life cycle cost summary of a reinforced concrete highway bridge

<table>
<thead>
<tr>
<th>Description</th>
<th>Carbon Steel</th>
<th>Epoxy C.S.</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Costs</td>
<td>8,197</td>
<td>31,420</td>
<td>88,646</td>
</tr>
<tr>
<td>Fabrication Costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other installation costs</td>
<td>15,611,354</td>
<td>15,611,345</td>
<td>15,611,354</td>
</tr>
<tr>
<td>Initial Costs</td>
<td>15,619,551</td>
<td>15,642,774</td>
<td>15,700,000</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Replacement</td>
<td>256,239</td>
<td>76,872</td>
<td>-141</td>
</tr>
<tr>
<td>Lost Production</td>
<td>2,218,524</td>
<td>2,218,524</td>
<td>0</td>
</tr>
<tr>
<td>Material related</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Operating Costs</td>
<td>2,247,763</td>
<td>2,295,396</td>
<td>-141</td>
</tr>
<tr>
<td><strong>Total LCC (USD)</strong></td>
<td><strong>18,094,314</strong></td>
<td><strong>17,937,170</strong></td>
<td><strong>15,699,859</strong></td>
</tr>
</tbody>
</table>
LCC Example: Roofing

Life cycle cost of a roof \(^{33, 34, 35}\)

Conventional roofing systems, \(~30\) years

Metal roofing system, 40-50 years

Stainless steel roofing system, more than 50 years
LCC Example: Roofing

Cost comparison of 0.6 mm coated galvanised carbon steel and 0.4 mm stainless steel grade 1.4401: Due to the mechanical properties of stainless steels, the material thickness can be reduced to 0.5 or 0.4 mm, providing a lighter weight (4.68 kg/m² for 0.7 mm coated carbon steel, 3.12 kg/m² for stainless steel). While coated carbon steel has a life expectation of 15 to 20 years, the service life of a stainless steel roof is generally that of the building.
Timeless Stainless Steel Architecture

Savoy hotel, London, 1929

Empire State building, New York, 1931

Chrysler Building, New York, 1930

Helix Bridge, Singapore, 2011

Petronas Towers, Kuala Lumpur

Cloud Gate “Jelly Bean”, Chicago, 2008
## Comparison of Life Cycle Costing

<table>
<thead>
<tr>
<th>Monument</th>
<th>Completed</th>
<th>Material</th>
<th>Height</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eiffel Tower – Paris</td>
<td>1889</td>
<td>Wrought iron</td>
<td>324m</td>
<td>Every 7 years. Every painting campaign lasts for about a year and a half (15 months). 50 to 60 tons of paint, 25 painters, 1500 brushes, 5000 sanding disks and 1500 sets of work clothes.</td>
</tr>
<tr>
<td>Chrysler Building (Roof and Entrance) – New York</td>
<td>1930 (roof 1929)</td>
<td>Austenitic Stainless Steel (302)</td>
<td>319m</td>
<td>Twice in 1951, 1961. The 1961 cleaning solution is unknown. A mild detergent, degreaser and abrasive were used in 1995.</td>
</tr>
</tbody>
</table>
What makes Stainless Steel “Green”?  
Stainless Steel Environmental Evaluation

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the recycled content?</td>
<td>60%</td>
</tr>
<tr>
<td>Is it 100% recyclable?</td>
<td>Yes</td>
</tr>
<tr>
<td>Does it provide long life?</td>
<td>Yes (reduces maintenance and disposal frequency)</td>
</tr>
<tr>
<td>Is there recycled content?</td>
<td>Yes (both post-consumer and post-industrial)</td>
</tr>
<tr>
<td>Is construction waste diverted from landfills?</td>
<td>Yes (high scrap value and product reuse potential)</td>
</tr>
<tr>
<td>Can it be salvaged and reused during renovations?</td>
<td>Yes</td>
</tr>
<tr>
<td>Is it a low emitting material?</td>
<td>Yes (no coatings = zero emissions)</td>
</tr>
<tr>
<td>Can it help to improve indoor air quality?</td>
<td>Yes (no volatile organic compounds (VOCs), bacteria removal, corrosion resistant ductwork)</td>
</tr>
<tr>
<td>Does it help to avoid the use of toxic materials?</td>
<td>Yes (long lasting termite barriers, minimal roof run-off)</td>
</tr>
<tr>
<td>Can it save energy?</td>
<td>Yes (sunscreens, roofing, balcony inserts)</td>
</tr>
<tr>
<td>Can it help generate clean energy?</td>
<td>Yes (solar panels, power plant scrubbers)</td>
</tr>
<tr>
<td>Can it conserve water?</td>
<td>Yes (corrosion and earthquake resistant water lines and tanks)</td>
</tr>
<tr>
<td>Can reflective panels add natural light?</td>
<td>Yes</td>
</tr>
<tr>
<td>Can it extend the life of other materials?</td>
<td>Yes (stone and masonry anchors, fasteners for wood and metals such as Al)</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- Sustainability is a big and important challenge for the future in the stainless steel industry. Efforts have been done to reduce its Carbon footprint by increasing recyclability and improving processes.
- Stainless steel have a combination of properties which should be taken into account in the decision-making process at the design state:
  - Mechanical properties
  - Corrosion resistance properties
  - Fire resistance
  - Recyclability
  - Long life
  - Low maintenance costs
  - Neutrality and Hygienic
  - Aesthetics
  - Neutrality to rain water
4. https://www.gsa.gov/portal/content/101197
5. Recycled content is defined in accordance with the ISO Standard 14021 -Environmental labels and declarations - Self declared environmental claims (Type II environmental labeling).
References and Sources (2/3)

15. ISSF [https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_and_CO2.pdf](https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_and_CO2.pdf). Data from European and Japanese ISSF members

16. Based on 2013 data, including 60% scrap content (and therefore 40% new materials) and energy contribution to GHG

17. Data provided by ISSF, estimates calculated by SCM. Includes 60% recycled content

18. ISSF [www.worldstainless.org](http://www.worldstainless.org). Data from European and Japanese ISSF members


22. C. Houska. Sustainable Stainless Steel Architectural.


25. Yale University/ISSF Stainless Steel Project, 2013


27. [https://www.nickelinstitute.org/Sustainability/LifeCycleManagement/LifeCycleAssessments/LCAProgressPier.aspx](https://www.nickelinstitute.org/Sustainability/LifeCycleManagement/LifeCycleAssessments/LCAProgressPier.aspx)


29. World Steel Association

References and Sources (3/3)

44. http://www.metsforbuildings.eu/
Thank you
Appendix
Recycling of other materials

This is a complex issue
This aims at giving a few ideas on other materials, for comparison purposes
Sources are indicated
More on recycling: Cement and Concrete


- 20% maximum of crushed concrete can be used in new concrete.
  - as aggregates only, not as cement
  - the concrete thus produced is a lower quality product, not suitable for all applications
- It seems that most of the concrete after demolition goes into road beds and landfill (no detailed figures are available)
- Crushing old concrete and transportation are the main operations in recycling, to be compared with getting aggregates locally.
- Overall, recycling involves everytime downcycling.
- Re-using concrete as blocks after demolition is only marginal today, but could provide the shortest route to re-use without downcycling. Not easy to implement, though!
More on recycling: plastics

http://www-g.eng.cam.ac.uk/impee/?section=topics&topic=RecyclePlastics&page=materials

- **In-house scrap** (generated at the source of production) is near-100% recycled already
- **Recycling of used plastics** is a big problem:
  - Collection is time-intensive, so expensive
  - Sorting of mixed plastic waste is difficult – contamination is inevitable.
  - Removing labels, print, all but impossible at 100% success rate
  - Contamination of any sort compromises re-use in “hi-tech” applications
    => recycled plastic (apart from in-house) is reused in lower-grade applications (downcycling): PET: cheap carpets, fleeces; PE and PP: block board, park benches.
    => and/or will be eventually burned or worse landfilled or even worse left floating on oceans.
More on recycling: Wood (from ABC*)

- The best recycling option is, of course, to re-use it. It appears that there is a lot of effort going on to collect, recondition and re-manufacture timber and other wood products. How much is re-used is not clear.
- Untreated timber and wood has found an increasing number of new uses: land and horticultural products, animal beddings, equestrian arena surfaces ...
- Treated timber& wood (the chemical treatment prevents rot, fungi, insects and UV damage) contains harmful chemicals, which strongly limit their use. The largest use has been so far particle board manufacture, but what happens to these boards at their end of life remains unclear.
- It should be pointed out that the overall deforestation going on on the planet does not speak for unlimited sources of new wood, especially in northern countries in which it takes a century for a tree to grow to its full size.
- Cutting down a forest and re-planting trees leaves the topsoil open to erosion for a while, and destroys the ecosystem in the harvested area possibly beyond self repair.
- Last, it has been argued that the carbon neutrality has been achieved only when the re-planted forest is fully grown....some 30 years or more later!

https://dtsc.ca.gov/toxics-in-products/treated-wood-waste/
https://woodrecyclers.org/about-waste-wood/wood-recycling-information/
http://en.wikipedia.org/wiki/Wood_preservation

*ABC: Architecture, Building and Construction
Thank you!

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6