Steel design

STEEL BEAM DESIGN Laterally Unrestrained Beam Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 1 Non-dimensional slenderness Beam behaviour analogous to yielding/buckling of columns. M Wyfy Material yielding (in-plane bending) MEd MEd Elastic member buckling Mcr Lcr 1. 0 Dr. A Aziz Saim 2010 EC3 Non-dimensional slenderness Unrestrained Beam ? LT 2 Lateral torsional buckling Lateral torsional buckling Lateral torsional buckling is the member buckling mode associated with slender beams loaded about their major axis, without continuous lateral restraint.

If continuous lateral restraint is provided to the beam, then lateral torsional buckling will be prevented and failure will occur in another mode, generally in-plane bending (and/or shear). Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 3 Eurocode 3 Eurocode 3 states, as with BS 5950, that both crosssectional and member bending resistance must be verified: MEd ? Mc , Rd Cross-section check (In-plane bending) MEd ? Mb, Rd Dr. A Aziz Saim 2010 EC3 Unrestrained Beam Member buckling check 4 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 5 Laterally Unrestrained Beam

The design of beam in this Lecture 3 is considering beams in which either no lateral restraint or only intermittent lateral restraint is provided to the compression flange Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 6 Lateral Torsional Buckling Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 7 Lateral Torsional Buckling Figure 3-1 shows an unrestrained beam subjected to load increment. The compression flange unrestrained and beam is not stiff enough. There is a tendency for the beam to deform sideways and twist about the longitudinal axis. The failure mode which may occur to the beam is called lateral torsional buckling.

Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 8 ? Involves both deflection and twisting rotation ? Out-of plane buckling. Bending Resistance M c, Rd ? M pl ? W pl f y ? M0 Due to the effect of LTB, the bending resistance of cross section become less. Failure may occurs earlier then expected Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 9 Examples of Laterally Unrestrained Beam Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 10 Restrained Beam Comparsion Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 11 Intermittent Lateral Restrained Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 12

Torsional restraint Usually both flanges are held in their relative positions by external members during bending. May be provided by load bearing stiffeners or provision of adequate end connection details. See Figure 3-4. Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 13 Beam without torsional restraint Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 14 Can be discounted when: • Minor axis bending • CHS, SHS, circular or square bar • Fully laterally restrained beams • ? LT < 0. 2 (or 0. 4 in some cases) - Unrestrained length Cross-sectional shape End restrained condition The moment along the beam Loading – tension or compression Unrestrained Beam 16

Dr. A Aziz Saim 2010 EC3 Lateral torsional buckling resistance Checks should be carried out on all unrestrained segments of beams (between the points where lateral restraint exists). Lateral restraint Lateral restraint Lcr = 1. 0 L Lateral restraint Beam on plan Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 17 Three methods to check LTB in EC3: • The primary method adopts the lateral torsional buckling curves given by equations 6. 56 and 6. 57, and is set out in clause 6. 3. 2. 2 (general case) and clause 6. 3. 2. 3 (for rolled sections and equivalent welded sections). The second is a simplified assessment method for beams with restraints in buildings, and is set out in clause 6. 3. 2. 4. • The third is a general method for lateral and lateral torsional buckling of structural components, given in clause 6. 3. 4. Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 18 Eurocode 3 states, as with BS 5950, that both cross-sectional and member bending resistance must be verified: MEd ? Mc , Rd Cross-section check (In-plane bending) MEd ? Mb, Rd Dr. A Aziz Saim 2010 EC3 Unrestrained Beam Member buckling check 19 Lateral-torsional buckling Eurocode 3 design approach for lateral torsional buckling is analogous to the olumn buckling treatment. The design buckling resistance Mb, Rd of a laterally unrestrained beam (or segment of beam) should be taken as: Mb, Rd ? ? LT Wy fy ? M1 Reduction factor for LTB Lateral torsional buckling resistance: Mb, Rd = ? LT Wy fy ? M1 Equation (6. 55) Wy will be Wpl, y or Wel, y ? LT Dr. A Aziz Saim 2010 EC3 is the reduction factor for lateral torsional buckling Unrestrained Beam 21 Buckling curves – general case (Cl 6. 3. 2. 2) Lateral torsional buckling curves for the general case are given below : (as in Eq (6. 56)) ? LT ? 1 2 ? LT ? ? LT ? ? 2 LT but ? LT ? 1. 0 ? LT ? 0. 5 [1 ? ? LT (? LT ? 0.) ? ? 2] LT Plateau length Imperfection factor from Table 6. 3 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 22 Imperfection factor ? LT Imperfection factors ? LT for 4 buckling curves: (refer Table 6. 3) Buckling curve Imperfection factor ? LT a 0. 21 b 0. 34 c 0. 49 d 0. 76 Buckling curve selection For the general case, refer to Table 6. 4: Cross-section Rolled I-sections Welded Isections Limits h/b ? 2 h/b > 2 h/b ? 2 h/b > 2 - Buckling curve a b c d d Other crosssections Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 24 LTB curves 4 buckling curves for LTB (a, b, c and d) 1. 2 Reduction factor ? LT . 0 0. 8 0. 6 0. 4 0. 2 0. 0 0 0. 5 1 1. 5 Curve a

Curve b Curve c Curve d 2 2. 5 0. 2 Dr. A Aziz Saim 2010 EC3 Non-dimensional slenderness Unrestrained Beam ? LT 25 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 26 lateral torsional buckling slenderness ? LT Mcr ? Wy f y Mcr Elastic critical buckling moment Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 27 Non-dimensional slenderness • Calculate lateral torsional buckling slenderness: ? LT ? Wy f y Mcr • Buckling curves as for compression (except curve a0) • Wy depends on section classification • Mcr is the elastic critical LTB moment Dr. A Aziz Saim 2010 EC3

Unrestrained Beam 28 BS EN 1993-1-1 does not give a method for determining the elastic critical moment for lateraltorsional buckling Mcr !!!!!!!! May use ‘ LTBeam’ software (can be downloaded from CTICM ?????? website) Or may use method presented by L. Gardner ……. Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 29 Mcr under uniform moment For typical end conditions, and under uniform moment the elastic critical lateral torsional buckling moment Mcr is: Mcr , 0 G IT Iw Iz Lcr ? EIz ? 2 Lcr 2 ? Iw Lcr GIT ? ? ? 2 ? ? EIz ? ? Iz 2 0. 5 is the shear modulus is the torsion constant is the warping constant is the inor axis second moment of area is the buckling length of the beam Unrestrained Beam 30 Dr. A Aziz Saim 2010 EC3 Mcr under non-uniform moment Numerical solutions have been calculated for a number of other loading conditions. For uniform doubly-symmetric cross-sections, loaded through the shear centre at the level of the centroidal axis, and with the standard conditions of restraint described, Mcr may be calculated by: ? EIz Mcr ? C1 2 Lcr 2 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam ? Iw Lcr GIT ? ? ? 2 ? ? EIz ? ? Iz 2 0. 5 31 C1 factor – end moments

For end moment loading C1 may be approximated by the equation below, though other approximations also exist. C1= 1. 88 – 1. 40y + 0. 52y2 but C1 ? 2. 70 where y is the ratio of the end moments (defined in the following table). Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 32 C1 factor – transverse loading Loading and support conditions Bending moment diagram Value of C1 1. 132 1. 285 1. 365 1. 565 1. 046 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 33 Design procedure for LTB Design procedure for LTB: 1. Determine BMD and SFD from design loads 2. Select section and determine geometry 3. Classify cross-section (Class 1, 2, 3 or 4) 4.

Determine effective (buckling) length Lcr – depends on boundary conditions and load level 5. Calculate Mcr and Wyfy Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 34 Design procedure for LTB 6. Non-dimensional slenderness ? LT ? Wy fy Mcr 7. Determine imperfection factor ? LT 8. Calculate buckling reduction factor ? LT 9. Design buckling resistance 10. Check Mb, Rd ? ? LT Wy fy ? M1 MEd ? 1. 0 Mb, Rd for each unrestrained portion Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 35 LTB Example General arrangement Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 36 LTB Example Design loading is as follows: 425. 1 kN A B C 319. 6 kN D 2. 5 m 3. 2 m 5. 1 m

Loading Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 37 LTB Example 267. 1 kN A B D 52. 5 kN SF C 477. 6 kN Shear force diagram B A C D BM 1194 kNm 1362 kNm Bending moment diagram Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 38 LTB Example For the purposes of this example, lateral torsional buckling curves for the general case will be utilised. Lateral torsional buckling checks to be carried out on segments BC and CD. By inspection, segment AB is not critical. Try 762? 267? 173 UB in grade S 275 steel. Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 39 LTB Example b z tw h d y y r z tf h = 762. 2 mm b = 266. 7 mm tw = 14. 3 mm tf = 21. 6 mm r = 16. mm A = 22000 mm2 Wy, pl = 6198? 103 mm3 Iz = 68. 50? 106 mm4 It = 2670? 103 mm4 Iw = 9390? 109 mm6 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 40 LTB Example For a nominal material thickness (tf = 21. 6 mm and tw = 14. 3 mm) of between 16 mm and 40 mm the nominal values of yield strength fy for grade S 275 steel (to EN 10025-2) is 265 N/mm2. From clause 3. 2. 6: N/mm2. E = 210000 N/mm2 and G ? 81000 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 41 LTB Example Cross-section classification (clause 5. 5. 2): e ? 235 / fy ? 235 / 265 ? 0. 94 Outstand flanges (Table 5. 2, sheet 2) cf = (b – tw – 2r) / 2 = 109. 7 mm cf / tf = 109. 7 / 21. 6 = 5. 8 Limit for Class 1 flange = 9e = 8. 48 > 5. 08 ? Flange is Class 1 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 42 LTB Example Web – internal part in bending (Table 5. 2, sheet 1) cw = h – 2tf – 2r = 686. 0 mm cw / tw= 686. 0 / 14. 3 = 48. 0 Limit for Class 1 web = 72 e = 67. 8 > 48. 0 ? Web is Class 1 Overall cross-section classification is therefore Class 1. Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 43 LTB Example Bending resistance of cross-section (clause 6. 2. 5): Mc , y, Rd ? Wpl, y fy ? M0 for Class 1 and 2 sec tions 6198 ? 103 ? 265 ? ? 1642 ? 106 Nmm 1. 0 ? 1642 kNm ? 1362 kNm ? Cross-section resistance in bending is OK.

Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 44 LTB Example Lateral torsional buckling check (clause 6. 3. 2. 2) – Segment BC: MEd ? 1362 kNm Mb , Rd ? ? LT Wy fy ? M1 where Wy = Wpl, y for Class 1 and 2 sections Determine Mcr for segment BC (Lcr = 3200 mm) Dr. A Aziz Saim 2010 EC3 ?

EIz Mcr ? C1 2 Lcr 2 ? Iw Lcr GIT ? ? ? 2 ? ? EIz ? ? Iz Unrestrained Beam 2 0. 5 45 LTB Example For end moment loading C1 may be approximated from: C1 = 1. 88 – 1. 40y + 0. 52y2 but C1 ? 2. 70 1194 y is the ratio of the end moments ? ? 0. 88 1362 ? C1 ? 1. 05 ? 2 ? 210000 ? 68. 5 ? 106 Mcr ? 1. 05 ? 32002 ? 9390 ? 109 32002 ? 81000 ? 2670 ? 103 ? ? ? 68. 5 ? 106 ? 2 ? 210000 ? 68. 5 ? 106 ? ? 0. 5 = 5699x106 Nmm = 5699 kNm Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 46 LTB Example Non-dimensional lateral torsional slenderness for segment BC: ? LT ? Wy fy Mcr 6198 ? 103 ? 265 ? ? 0. 54 6 5699 ? 10 Select buckling curve and imperfection factor ? LT: From Table 6. 4: h/b = 762. 2/266. 7 = 2. 85 For a rolled I-section with h/b > 2, use buckling curve b Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 47 LTB Example From Table 6. 3 of EN 1993-1-1: For buckling curve b, ? LT = 0. 34 Calculate reduction factor for lateral torsional buckling, ? LT – Segment BC: ? LT ? 1 ? LT ? ? 2 LT ?? LT but ? LT ? 1. 0 where ? LT ? 0. 5 [1 ? ? LT (? LT ? 0. 2) ? ? 2] LT Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 48 LTB Example ? LT = 0. 5[1+0. 34(0. 54-0. 2) + 0. 542] = 0. 70 ? ? LT ? 1 0. 70 ? 0. 70 ? 0. 54 2 2 ? 0. 87 Lateral torsional buckling resistance Mb, Rd – Segment BC : Mb, Rd ? ? LT Wy fy ? M1 265 ? 0. 87 ? 6198 ? 10 ? 1 . 0 3 ? 1425 ? 106 Nmm ? 1425 kNm Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 49 LTB Example MEd 1362 ? ? 0. 96 ? 1. 0 ? Segment BC is OK Mb, Rd 1425 Lateral torsional buckling check (clause 6. 3. 2. 2) – Segment CD: MEd ? 1362 kNm Mb , Rd ? ? LT Wy fy ? M1 where Wy = Wpl, y for Class 1 and 2 sections

Determine Mcr for segment CD (Lcr = 5100 mm) Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 50 LTB Example ? EIz Mcr ? C1 2 Lcr 2 ? Iw Lcr GIT ? ? ? 2 ? Iz ? EIz ? ? 2 0. 5 Determine y from Table: 0 y is the ratio of the end moments ? ? 0 1362 ? C1 ? 1. 88 ? 2 ? 210000 ? 68. 5 ? 106 Mcr ? 1. 88 51002 ? 9390 ? 109 51002 ? 81000 ? 2670 ? 103 ? ? ? ? 68. 5 ? 106 ? 2 ? 210000 ? 68. 5 ? 106 ? ? 0. 5 = 4311? 106 Nmm = 4311 kNm Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 51 LTB Example Non-dimensional lateral torsional slenderness for segment CD: ? LT ? Wy fy Mcr 6198 ? 103 ? 265 ? ? 0. 62 6 4311? 10 The buckling curve and imperfection factor ?

LT are as for segment BC. Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 52 LTB Example Calculate reduction factor for lateral torsional buckling, ? LT – Segment CD: ? LT ? 1 ? LT ? ? 2 LT ?? 2 LT but ? LT ? 1. 0 where ? LT ? 0. 5 [1 ? ? LT (? LT ? 0. 2) ? ? 2] LT = 0. 5[1+0. 34(0. 62-0. 2) + 0. 622] = 0. 76 ? ? LT Dr. A Aziz Saim 2010 EC3 ? 1 0. 76 ? 0. 76 ? 0. 62 2 Unrestrained Beam 2 ? 0. 83 53 LTB Example Lateral torsional buckling resistance Mb, Rd – Segment CD : Mb, Rd ? ? LT Wy fy ? M1 265 ? 0. 83 ? 6198 ? 10 ? 1. 0 3 ? 1360 ? 106 Nmm ? 1360 kNm MEd 1362 ? ? 1. 00 Mb, Rd 1360 Segment CD is critical and marginally fails LTB check.

Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 54 Blank Page Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 55 Simplified assessment of ? LT For hot-rolled doubly symmetric I and H sections without destabilising loads,? may be conservatively simplified to: LT ? LT ? 1 0. 9 ? z ? C1 ? z 1 0. 9 ? 1 C1 E ? z ? L / iz ; ? 1 ? ? fy As a further simplification, C1 may also be conservatively taken = 1. 0. Simplified assessment of ? LT Substituting in numerical values for simplified expressions result. ? 1 , the following S235 ? LT ? 1 L / iz C1 104 S275 ? LT ? 1 L / iz C1 96 S355 ? LT ? 1 L / iz C1 85 C1 may be conservatively taken = 1. , though the level of conservatism increases the more the actual bending moment diagram differs from uniform moment.

Simplified method (Cl. 6. 3. 2. 4) Simplified method for beams with restraints in buildings (Clause 6. 3. 2. 4) This method treats the compression flange of the beam and part of the web as a strut: b b Compression h Tension Compression flange + 1/3 of the compressed area of web Strut Dr. A Aziz Saim 2010 EC3 Beam Unrestrained Beam 58 General method (Cl. 6. 3. 4) General method for lateral and lateral torsional buckling of structural components • May be applied to single members, plane frames etc. Requires determination of plastic and elastic (buckling) resistance of structure, which subsequently defines global slenderness • Generally requires FE Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 59 Blank Page Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 60 Important Notes: (End Connections) When full torsional restraint exist: -both the compression and tension flanges are fully restrained against rotation on plan -both flanges are partially restrained against rotation on plan - both flanges are free to rotate on plan Unrestrained Beam 61 Dr. A Aziz Saim 2010 EC3 Connection Detail

Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 62 Important Notes: (End Connections) Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 63 Important Notes: (End Connections) When both flanges are free to rotate on plan and the compression flange is unrestrained: i. torsional restraint is provided solely by connection of the tension flange to the supports, ii. torsional restraint is provided solely by dead bearing of the tension flange on support. Unrestrained Beam 64 Dr. A Aziz Saim 2010 EC3 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 65 Dr. A Aziz Saim 2010 EC3 Unrestrained Beam 66